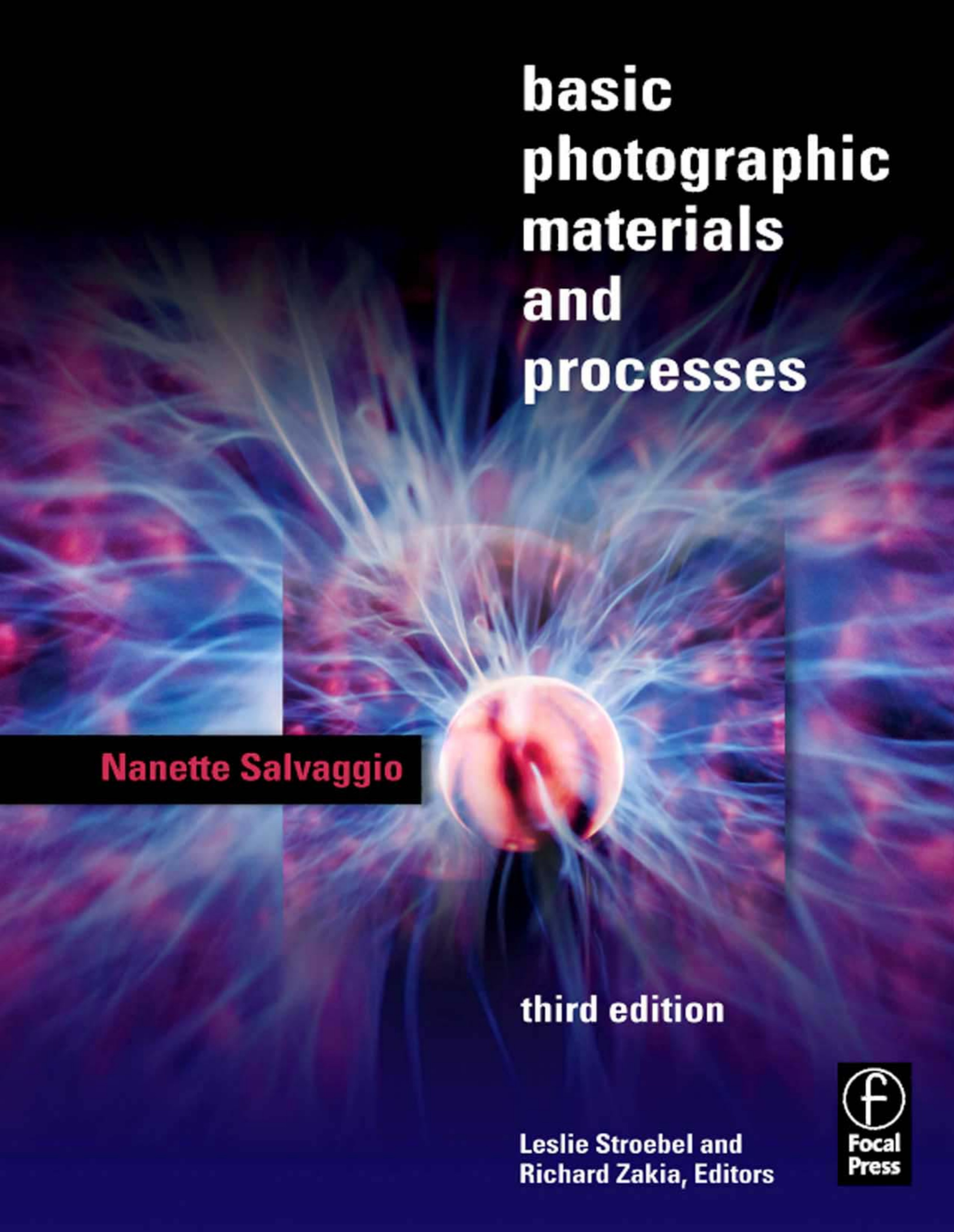

basic photographic materials and processes

Nanette Salvaggio

third edition

Leslie Stroebel and Richard Zakia, Editors

Focal Press

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THIRD EDITION

Nanette Salvaggio

Dr. Leslie Stroebel and
Dr. Richard Zakia, Editors

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Contents

Preface

This revision is a bridge between the classic world of film photography and the new world of digital imaging. Just as the class this book was originally written for, Materials and Processes of Photography here at the Rochester Institute of Technology, is slowly moving from a film-based class to a digital-based class, so, too, is this text. However, as a student of Dr. Leslie Stroebel's from days gone by, I will never be able to remove film totally from its pages. As I have found in teaching this class over the past four years, first learning about film in all its glory allows students to gain a deeper understanding of the digital world. The classic knowledge provides them with insight into how to get the most out of every pixel they capture from making an exposure to printing the final image.

My hope is that this is the first in several revisions over the coming years that will allow the knowledge held within these pages to change at a similar pace with the rapidly changing field of digital photography. I also hope that the students who use this book will find the mixture of the old and new intriguing and helpful on their journey from wide-eyed young freshman to the successful photographers of tomorrow. As you will see from the many images some of my students have provided for the pages of this book, many are already well on their way.

I have to thank my incredible husband Carl, for his support during the past months while I spent many hours working on this book. I also have to thank my son, Philip, who assisted in capturing many of the figures here. Without this help, I would never have finished in time.

I extend my deep appreciation to Paul Schwartz for rescuing me in the area of black-and-white development and chemistry. I also would like to acknowledge all of the students and faculty members who provided images, starting with our new cover. Credit for this photograph goes to Noelle Pensec, a Biomedical Photographic Communications student here at Rochester Institute of Technology. She captured this image for an assignment—the goal was to create an image that could be a book cover. I also need to acknowledge my colleagues and students Brandon Balch, Derrick Clark, James Craven, Andy Davidhazy, Stephen Diehl, Oscar Durand, KT Evans, David Filiberti, Douglas Gaston IV, David Kelbe, Elliot Krasnopoler, Robert Lussen, Glenn Miller, Michael Peres, Jessica Peterson, Sarah Priestap, Lydia Richards, Jessica Scott, Josh Shagam, Natalie Sinisgalli and Rob Weber for so graciously contributing their photographs to my effort.

Regards, Nanette

Foreword

A Brief History of Photography

It might be said that photography, as a new way of making images, had its beginnings as early as 1816 when Joseph Nicéphore Niépce succeeded in producing a camera image on light-sensitive silver-chloride paper. Unfortunately, he was not able to fix the image, so there is no pictorial record of his accomplishment. The oldest preserved photographic image, made by Niépce in 1827, is housed at the University of Texas in Austin in the Gernsheim Collection.

In 1833 a Brazilian, Hercules Florence, produced images on paper sensitized with silver salts and coined the word *photography.* It wasn't until 1973, however, that his achievements were recognized.

Louis Jacques Mande Daguerre, who began a partnership with Niépce in 1829, went on to invent and announce, in January 1839, his daguerreotype process. The daguerreotype was a laterally reversed positive monochrome image on a polished silver-coated copper plate. The image was one of a kind and was not reproducible.

Henry Fox Talbot, having learned of the announcement by Daguerre, decided to announce his Talbotype process that he had developed earlier in 1835. The Talbotype produced a monochromatic image on sensitized paper that was both tonally and laterally reversed. Because the image was a negative, it was contact printed onto another piece of sensitized paper with sunlight to produce a positive image.

Following the introduction of photography in the first half of the 1800s, a progression of important advances appeared—wet-collodion emulsions on glass plates, dry silver-halide emulsions on flexible film, albumen from egg whites to suspend the silver salts—to be replaced in turn by gelatin, noncombustible (safety) film base materials, higher-speed films followed by finer-grain fast films, orthochromatic, panchromatic, and infrared emulsion sensitivity, reversal and negative color films and papers, and false-color films, instant-picture processes—to mention only a sample of the revolutionary innovations that have been introduced.[1] Truly, the period from the middle of the nineteenth century to the end of the twentieth century produced the impressive high-tech chemical evolution in photographic imaging. Now, a dramatic shift from high-tech chemical to high-tech electronic imaging is taking place.

The closing years of the twentieth century and the beginning years of the twenty first century have seen an explosive interest in digital photography, Although the technology of digital imaging is new, most of the basic concepts involved in digital photography—from the characteristics of the light illuminating and reflected from the subject, to the process of forming an optical image, to the sensitometric

[1]For a more comprehensive list covering the period from the 1200s to 1991, see: *The Focal Encyclopedia of Photography,* 3rd ed. s.v. "advances in photographic technology."

and colorimetric characteristics of the digital image, to the visual perception of the final image—remain the same.

Some of the major advantages of a digital image are that the captured image can be seen immediately, can easily be manipulated and transformed, and can easily be sent over the internet to potentially anywhere in the world including vehicles and stations in outer space.

A Brief History of Photographic Education

Early photographers were mostly self-taught. If they became successful professional photographers, they might take on an apprentice who received on-the-job training and serve as an assistant for very little pay, but there were no schools of photography. Eventually, some high schools and colleges offered one or more courses in photography, typically in the art department, but no college offered a degree program with photography as a major.

In 1927, C. B. Neblette wrote an article entitled "A Photographic Dream" that was published in *Photo-Era Magazine,* in which he is the head of the school of photography at Bernard University and talks to a group of visitors who are interested in what they have accomplished in their courses in technical and scientific photography. He tells them that all applied photography is based upon knowledge of the fundamental theories of the science, and that knowledge of photography can be applied to any scientific professional field. The first year of their two-year program is devoted to the fundamental principles of the science. The course consists of two hours of lectures and four hours of laboratory work each week. He then takes the group on a tour of their studios and darkrooms, well equipped with donations from the manufacturers, and describes what the students will study in each year of the program. At the end of his presentation, the sound of a ringing telephone wakened him—it was only a dream—but he went on to live his dream in Rochester, NY.

Neblette preferred to be known as C.B., rather than Carol Bernard. He wrote many articles and gave many speeches on the need for colleges to recognize photography as a legitimate major of study. His first book, *Photography, Its Materials and Processes,* published in 1927, was widely recognized as a major contribution to photography and photographic education. In the preface, Neblette wrote that his aim was to present as concisely as possible the fundamental principles of the science of photography. Five more editions of *Photography, Its Materials and Processes* followed the classic first edition, and a 7th edition in this series of books was retitled *Materials and Processes of Photography.* He was an honorary fellow of the Royal Photographic Society of Great Britain and vice president for education with the Society of Photographic Scientists and Engineers. He became known as the father of photographic education.

The Rochester Athenaeum and Mechanics Institute, later to become R.I.T., offered its first day and evening classes in photography in 1902. A full program in photography was introduced in 1930, and R.A.M.I. remained the only college in the country to offer college-level photography programs for many years. Fred Brehm and C. B. Neblette were reassigned from Eastman Kodak to the R.A.M.I. School of Photography on a part time basis, with both later becoming full time faculty members, and Neblette

later becoming director. He implemented a three year diploma program that included both professional and technical photography courses, and an optional work-study program. A new building was erected during WWII for the School of Photographic Arts and Sciences (SPAS) and the School of Printing, to accommodate returning veterans who would enroll with the help of the G.I. Bill, and the name R.A.M.I. was changed to Rochester Institute of Technology (R.I.T.). Over the following years, associate, bachelor, and master degree programs were introduced, and the number of departments offering specialized programs in a wide range of photographic fields increased dramatically.[2] In 1968, R.I.T. moved from a thirteen-acre downtown campus to a thirteen-hundred-acre campus on the outskirts of the city.

Surveys conducted in recent years reveal that more than three hundred schools in the United States now offer degree programs in photography with studies in a wide range of photographic subjects. Over sixty schools offer graduate degrees, most leading to an M.F.A. degree in photography. The Rochester Institute of Technology offers the most comprehensive range of degree programs in photographic studies.[3]

A Brief History of This Book

After C.B. Neblette retired as dean of the college of Graphic Arts and Photography in 1968, Professors Leslie Stroebel, John Compton, Ira Current, and Richard Zakia wrote *Photographic Materials and Processes* in 1986.[4] Realizing the need for a more basic book, the authors published *Basic Photographic Materials and Processes* in 1990, and the second edition in 2000. This new third edition reflects the continued growth of the science of photography by weaving in digital concepts throughout and including an entire chapter strictly on digital photography.

We are grateful to Nanette Salvaggio, a member of the photographic faculty at R.I.T., for the care she took in updating each chapter in the book for this third edition with relevant digital information including a whole new chapter strictly on digital photography.

Drs. Leslie D. Stroebel and
Richard D. Zakia
Professors Emeriti, Rochester
Institute of Technology

[2] Over a hundred Photographic Fields are listed under that heading in *The Focal Encyclopedia of Photography,* Third Edition, page 583.
[3] See Photographic Education in *The Focal Encyclopedia of Photography,* Third Edition, pages 565–579, for more detailed information revealed in the surveys
[4] Awarded Honorable Mention in the Kraszna-Krause Foundation/Book Trust International.

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chapter 1

Light and Photometry

"Streaming Lights" by Caitlin Shannon, 2007, Biomedical Photographic Communications student, Rochester Institute of Technology

I think George Eastman said it best, "*Light makes photography. Embrace light. Admire it. Love it. But above all, know light. Know it for all you are worth, and you will know the key to photography*." So it is here we will start, with light and photometry.

The Nature of Light

Light is defined as the radiant energy that our visual system, our eyes, is sensitive to and depends upon for the sensation of vision.

Light is fundamental to photography. The function of photographic materials and digital sensors is to capture light and record the patterns it creates. The equipment we use to create images are lamps to produce light, exposure meters and color temperature meters, to measure and characterize the light and lenses, shutters, apertures and filters to control light. The study of photography must begin with understanding light.

The importance of light is obvious. Light has been the object of an enormous number of experiments and studies over many centuries. Isaac Newton was one of the first persons to make significant headway in understanding the nature of light. In the seventeenth century, Newton performed a series of experiments and proposed that light is emitted from a source in straight lines as a stream of particles.

Light travels about 25,000 miles in 1/10 of a second. Sound would require about 33 hours to travel the same distance.

This theory was called the *corpuscular theory*.

Any photographer knows that light bends when it passes from one medium to another, and that light passing through a very small aperture tends to spread out. These facts are not easily explained by the corpuscular theory. As a result, Christian Huygens proposed the *wave theory*, which stated that light and similar forms of electromagnetic radiation are transmitted as a waveform in some media. In the nineteenth century, Thomas Young performed a number of experiments that also supported the wave theory of light. The wave theory satisfactorily explained many of the phenomena associated with light that the corpuscular theory did not, but it still did not explain all of them.

One of the more notable unexplained effects is the behavior of *blackbody radiation*. Blackbody radiation is radiation produced by a body that absorbs all the radiation that strikes it, and emits radiation by incandescence, depending on its temperature. In 1900, Max Planck suggested the hypothesis of the "quantization of energy" to explain the behavior of blackbody radiation. This theory states that the only possible energies that can be possessed by a ray of light are integral multiples of a quantum of energy.

In 1905, Albert Einstein proposed a return to the corpuscular theory of light with light consisting of photons, each photon containing a quantum of energy. These suggestions, along with others, gradually developed into what is known today as *Quantum Theory* or *Quantum Electrodynamics*. This theory combines aspects of the corpuscular and wave theories, and satisfactorily explains all of the known behavior of light.

Unfortunately, this theory is difficult to conceptualize, and can be rigorously explained only by the use of sophisticated mathematics. As a result, the corpuscular and wave theories are still used to some extent where simple explanations of the behavior of light are required.

Light Waves

If we accept the idea that light moves as a wave function, it is necessary to determine the nature of the waves and the relationship of light to other forms of radiation. Actually, light is a fractional part of a wide range of radiant energy that exists in the universe, all of which can be thought of as traveling in waves. These forms of energy travel at the tremendous speed of approximately 186,000 miles (3×10^8 meters) per second. They differ only in wavelength and frequency of vibration. These waves have been shown to vibrate at right angles to their path of travel. The distance from the crest of one wave to the crest of the next is termed the *wavelength* represented by the Greek letter lambda (λ). Figure 1-1 illustrates this concept. The number of waves passing a given point in a

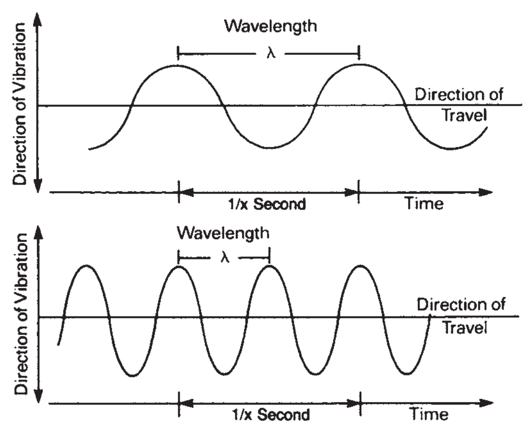

Figure 1-1 A simple form of a light wave, illustrated in a longitudinal cross section. In reality, the wave is vibrating in all possible right angles to the direction of travel. The second wave has a wavelength one-half that of the first and, therefore, a frequency twice as great.

second is called the *frequency of vibration*; the symbol f is used to specify it. The wavelength multiplied by the frequency of vibration equals the speed or velocity (symbol v) of the radiation. Thus, $\lambda \times f = v$.

Since the wavelength of radiant energy can be determined with far greater accuracy than the frequency, it is common practice to specify a particular type of radiation by its wavelength. Because of the extreme shortness of the wavelengths encountered with light sources, the most frequently employed unit of measure is the nanometer (nm), which is equal to one-billionth of a meter. A somewhat less commonly used measure is the Angstrom (Å), which is equal in distance to 1/10 of a nanometer (e.g., 400 nm equals 4,000 Å). Table 1-1 summarizes these measurement concepts.

The Electromagnetic Spectrum

When the various forms of radiant energy are placed along a scale of wavelengths, the resulting continuum is called the *electromagnetic spectrum*. Although each form of radiant energy differs from its neighbors by an extremely small amount, it is useful to divide this spectrum into the generalized categories shown in Figure 1-2. All radiations are believed to be the result of electromagnetic oscillations. In the case of radio waves, the wavelengths are extremely long, being on the order of 1010 nm, and are the result of long electrical oscillations. The fact that such energy permeates our environment can easily be demonstrated by turning on a radio or television receiver in any part of the technologically developed world. This form of radiant energy is not believed to have any direct effect upon the

Table 1-1 Units of length

Unit	Symbol	Length
Meter	m	3.218 ft. (38.6 in.)
Centimeter	cm	0.01 m (10^{-2} m)
Millimeter	mm	0.001 m (10^{-3} m)
Micrometer	μ (mu)	0.000001 m (10^{-6} m)
Micron	μ (mu)	0.000001 m (10^{-6} m)
Nanometer	nm	0.000000001 m (10^{-9} m)
Millimicron	mμ	0.000000001 m (10^{-9} m)
Angstrom	Å	0.0000000001 m (10^{-10} m)

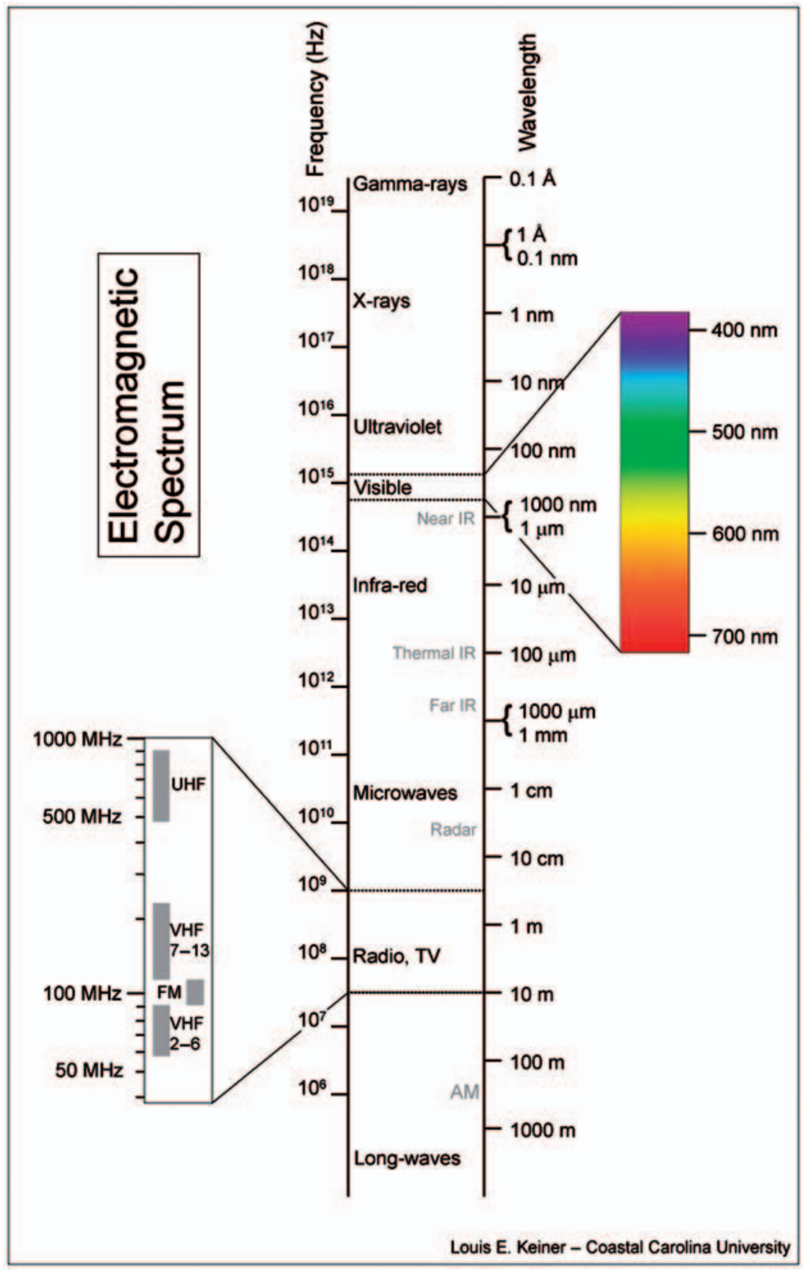

Figure 1-2 The electromagnetic spectrum.

The temperature of −273°C is referred to as absolute zero or 0 Kelvin (K), after Lord Kelvin, who first proposed such a scale.

Although the terms *UV light* and *black light* are commonly seen in print, *UV radiation* is a more appropriate term.

Light occupies a very small part of the electromagnetic spectrum generally from 400 to 700 nm.

human body. Radio waves are customarily characterized by their frequency, expressed in hertz (cycles per second).

The portion of the electromagnetic spectrum that we sense as heat is called the *infrared region*. The origin of this type of radiant energy, which is shorter in wavelength than radio waves, is believed to be the excitation of electrons by thermal disturbance. When these electrons absorb energy from their surroundings, they are placed in an elevated state of activity. When they suddenly return to their normal state, electromagnetic radiation is given off. It has been shown that any object at a temperature greater than −273° C will give off this type of radiation. Thus, all the objects we come into contact with give off some infrared energy. In general, the hotter an object, the more total energy it produces and the shorter the peak wavelength.

If an object is heated to a high enough temperature, the wavelength of the energy emitted will become short enough to stimulate the retina of the human eye and cause the sensation of vision. It is this region of the electromagnetic spectrum that is termed light. Notice that it occupies only a narrow section of the spectrum between approximately 380 and 720 nm. Because the sensitivity of the human visual system is so low at these limits, 400 and 700 nm are generally considered to be more realistic values. Objects with very high temperatures produce ultraviolet energy, which is shorter than 400 nm in wavelength.

To produce radiant energy shorter in wavelength than about 10 nm requires that fast-moving electrons bombard the object. When these rapidly moving electrons strike the object, the sudden stopping produces extremely short wave energy called *X-radiation*, or more commonly, *X-rays*. Still-shorter wavelengths can be produced if the electron bombardment intensifies, as occurs in a cyclotron. In addition, when radioactive material decomposes, it emits energy shorter in wavelength than X-rays. In these two cases, the energy is referred to as *gamma rays*, which are usually 0.000001 nm (10^{-6} nm) in wavelength and shorter. These forms of electromagnetic energy are the most energetic, penetrating radiation known.

Thus it can be seen that the wave theory of radiant energy provides a most useful system for classifying all the known forms of radiation.

The Visible Spectrum

The wavelengths of energy referred to as light are located near the middle of the electromagnetic spectrum. It is important to note that the location of this region is solely dictated by the response characteristics of the human eye. In fact, the international standard definition states: “Light is the aspect of radiant energy of which a human observer is aware through the visual sensations that arrive from the stimulation of the retina of the eye.” Simply stated, light is the energy that permits us to see. By definition, all light is visible, and for this reason the word *visible* is an unnecessary (and perhaps confusing) adjective in the common expression *visible light*. This definition also may be interpreted to mean that energy that is not visible cannot and should not be called light. Thus it is proper to speak of *ultraviolet radiation* and *infrared radiation*, not ultraviolet light and infrared light. The popular use of such phrases as *black light* and *invisible light* to describe such radiation makes it impossible to determine what type of energy is being described and should be avoided.

To understand more about light, it is necessary to become familiar with

the way the human eye responds to it. Figure 1-3 represents the photopic luminosity function of the human eye as defined by the International Commission on Illumination (CIE). The plot illustrates the sensitivity of the eye to different wavelengths (or colors) of light. These data indicate that the sensitivity of the eye drops to near zero at both 400 and 700 nm, thus specifying the limits within which radiant energy may be referred to as light. It also shows that the response of the eye is not uniform throughout the visible spectrum. Human vision is most sensitive to green light. If equal physical amounts of different colors of light are presented to an observer, the green portion of the spectrum would appear the brightest, and the blue and red parts would appear very dim. This is the reason that a green safelight is used when processing panchromatic film. Since the eye is most sensitive to green light, it takes less of it to provide adequate visibility in the darkroom than any other color of light.

The plot shown in Figure 1-3 has been accepted as an international standard response function for the measurement of light. Therefore, any meter intended for the measurement of light must possess a sensitivity function identical to it. Most photoelectric meters used in photography have response functions significantly different from the standard and are not properly called light meters, although the international standard curve can be approximated by the use of appropriate filters with some meters. (It is worth noting that the determination of the proper *f*-number and shutter speed for a given photographic situation does not require a meter with this response function. It is more important for the meter to match the sensitivity of the film or digital sensor being used than that of the human eye.)

When all of the wavelengths between 400 and 700 nm are presented to the eye in nearly equal amounts, the light is perceived as white. There is no absolute standard for white light because the human visual system easily adapts to changing conditions in order to obtain the perception of whiteness. For example, the amounts of red, green, and blue light in daylight are significantly different from those of tungsten light; however, both can be perceived as white due to physiological adaptation and the psychological phenomenon known as *color constancy*. (See Figure 1-4.) Thus our

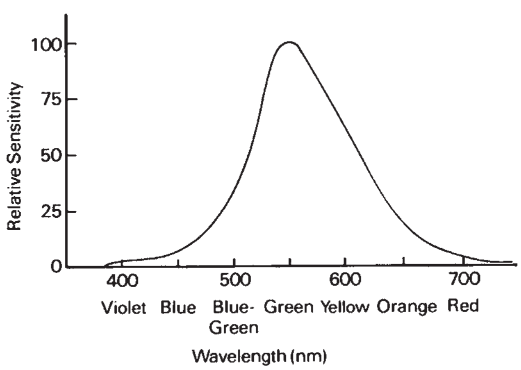

Figure 1-3 The sensitivity curve of the human eye. The plot indicates the relative brightness of the energy at each wavelength.

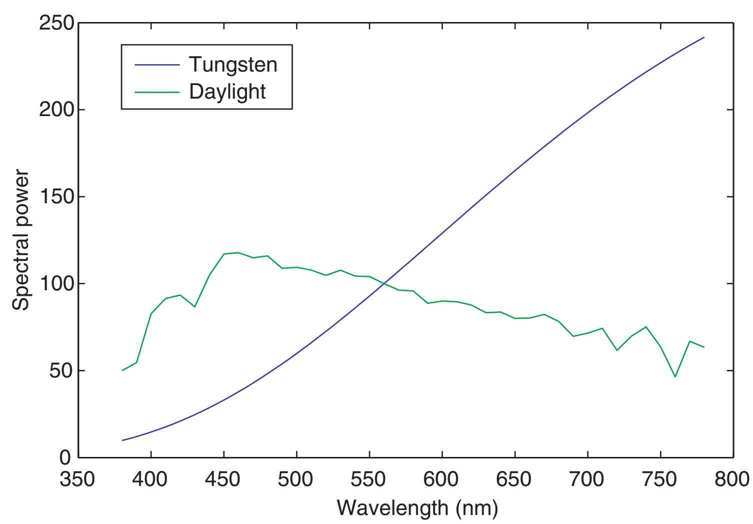

Figure 1-4 Spectral power distributions of a tungsten and daylight light source.

eyes easily adapt to any reasonably uniform amount of red, green, and blue light in the prevailing illumination. This means that our eyes are not reliable for judging the color quality of the prevailing illumination for the purposes of color photography.

If a beam of white light is allowed to pass through a glass prism as illustrated in Figure 1-5, the light is dispersed into a series of colors we call the *visible spectrum*. This separation of colors occurs because lights of varying wavelengths are bent by different amounts. The shorter-wavelength blue light is bent to a greater extent than the longer-wavelength green and red light. The result is a rainbow of colors that range from a deep violet to a deep red. Experiments indicate that human observers can distinguish nearly one hundred different spectrum colors. However, the visible spectrum is often arbitrarily divided into the seven colors listed in Figure 1-5.

To describe the properties of color photographic systems in simple terms, the spectrum is divided into just three regions: red, green, and blue. The color of the light may also be specified at a given wavelength, thereby defining a spectral color. Such colors are the purest possible because they are unaffected by mixture with light of other wavelengths. It is also possible to specify a certain region or color of the spectrum by the bandwidth of the wavelengths. For example, the red portion of the spectrum could be specified as the region from 600 to 700 nm.

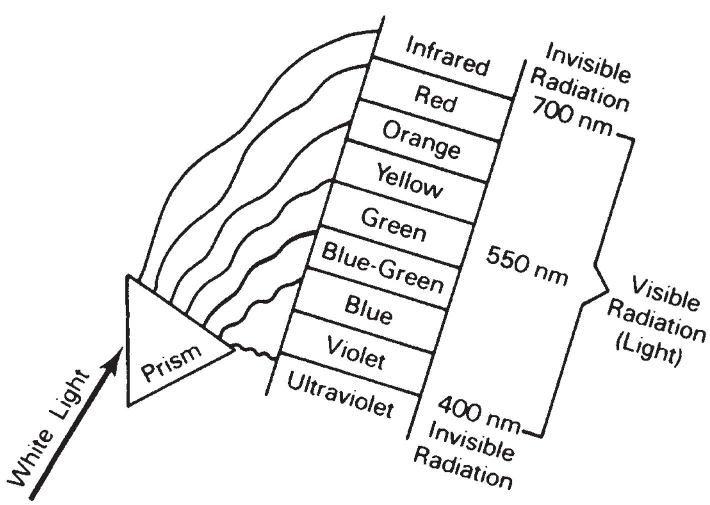

Figure 1-5 The dispersion of white light into the visible spectrum.

Spectral Power Distributions

All forms of light can be identified by their spectral power distributions. If we accept that white light can be dispersed into the individual wavelengths of visible spectrum as illustrated in Figure 1-5, then it follows that it can also be measured at each of these wavelengths. When this is done the resulting measurement is called a *spectral power distribution* (SPD). An SPD is measured with a spectrophotometer, which measures a light source as a function of wavelength. Figure 1-3, seen previously, provides the SPD for a tungsten and a daylight light source. Notice that the tungsten light source is smooth and is referred to as a continuous light source. It simulates a blackbody radiator.

Planck's equation (Eq. 1-1) can be used to determine the SPD of a blackbody radiator at any temperature. As can be seen in the equation, all the terms are constant except for wavelength.

$$\mathrm{M} = \frac{2hc^2}{\lambda^5\left(e^{hc/\lambda kT} - 1\right)} \quad \text{(Eq. 1-1)}$$

where h is Planck's constant of $6.6262 \cdot 10^{-34}$ *J-s*

c is the speed of light with a value of $2.9979 \cdot 10^8\,\mathrm{m/s}$

λ is the wavelength of energy in meters

k is Boltzmann's constant of $1.3807 \cdot 10^{-23}\ J/K$, and
T is the absolute temperature of the light source in degrees Kelvin.

Solid-Object Sources and the Heat-Light Relationship

Light is a form of energy that can only be produced from some other form of energy. The simplest and perhaps most common method is from heat energy, a process called incandescence. Whether the source is the filament in a tungsten lamp, a candle flame, or anything that has been heated until it glows, incandescence is always associated with heat. The amount and color of light produced by an incandescent source is directly related to the temperature to which it is heated. Consider, for example, an iron poker with one end placed in a fire. Holding the end of the poker in the fire, it is cold, but as it is left in the fire its temperature rises and it begins to feel warm. By increasing the temperature of the poker, we become aware of a change in its radiating properties through our sense of touch, although it looks the same. Soon the poker will become too hot to touch, and we will be able to sense its radiation as heat at a short distance. As the temperature is raised even higher, the poker reaches its point of incandescence and begins to emit a deep red glow. If the poker is allowed to get hotter still, the color of the light it produces will become more yellowish, and the light will become brighter. At extremely high temperatures, the end of the poker will look white, and ultimately blue, in addition to becoming still brighter. All of this illustrates that a solid object heated to its point of incandescence and higher will produce light that varies in color as a function of its temperature. When describing the temperature of such sources, it is common practice to employ the absolute or Kelvin scale because all objects emit some infrared energy at temperatures above absolute zero.

The best solid-object radiator is a black body, as it absorbs all the energy that strikes it. All light sources are radiators, some of which are more efficient than others. Thus, since a perfectly black object would absorb and emit energy but not reflect it when heated, it would be the most efficient source. A blackbody source is achieved in practice by the design shown in Figure 1-6. An enclosure surrounded by a boiling material becomes the source. Since the interior surface of the object is darkened and everywhere concave, any light that enters will be absorbed, either immediately or after one or more reflections. Consequently the hole will appear perfectly black. As the walls of the oven are heated, they will emit radiant energy in all directions. The energy that escapes through the hole is called *blackbody radiation*. When such an experiment is performed and the blackbody is heated to a variety of temperatures, the characteristics of

Two hundred years before Newton, Leonardo da Vinci discovered that white light contains different colors, but he identified only five colors.

All objects emit radiation at room temperature, but objects must be heated to a temperature of approximately 12,000° Fahrenheit before visible radiation is emitted.

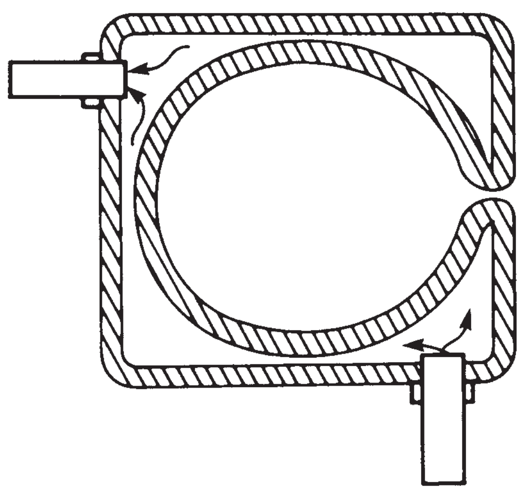

Figure 1-6 Cross section of a simple blackbody radiator consisting of an enclosure surrounded by boiling or molten material.

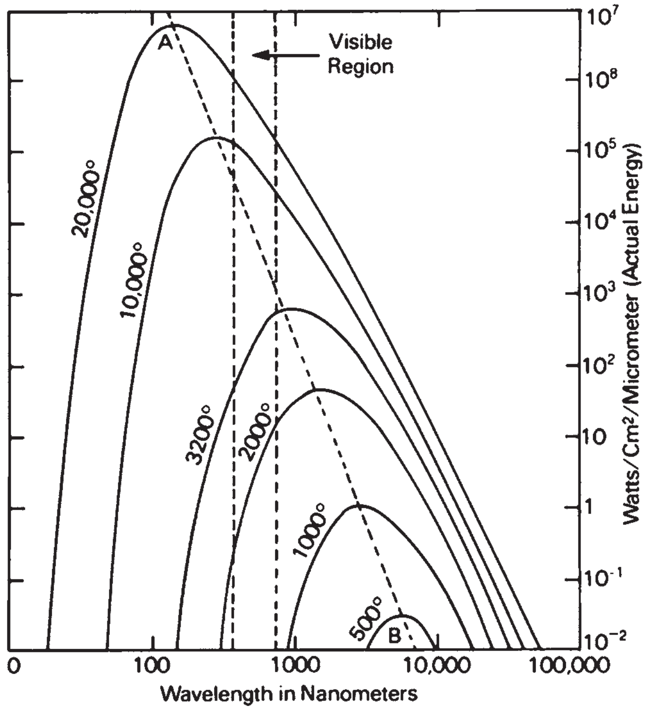

Figure 1-7 Spectral-energy curves for a blackbody at various temperatures.

Emissivity is the ratio of energy radiated by a material to the energy radiated by a blackbody at the same temperature.

the radiant energy it produces change systematically, as shown in Figure 1-7. Each individual curve is often referred to as a spectral power distribution (SPD). An SPD provides the level of radiant power emitted by the source at each wavelength.

As discussed previously, every object emits energy from its surface in the form of a spectrum of differing wavelengths and intensities when heated to temperatures greater than −273° C (absolute zero). The exact spectrum emitted by the object depends upon its absolute temperature and its emissivity (the ratio of energy radiated by a material to the energy radiated by a blackbody at the same temperature). Since the blackbody has perfect emissivity ($\varepsilon=1$), the temperature in degrees Kelvin becomes the only important factor. Figure 1-7 shows that as the temperature increases, each curve increases everywhere, indicating that the amount of energy at each wavelength increases. As the temperature increases, the peak output wavelength becomes shorter. The peak position shifts from the long-wavelength end of the infrared region toward the short-wavelength end of the ultraviolet region as the temperature increases. The portion of emitted energy that would be perceived as light is contained within the narrow band between the broken lines.

Solids emit continuous spectrums. Gases and vapors emit discontinuous spectrums.

We have enough knowledge to make some observations now. First, all objects we are likely to encounter are at temperatures greater than −273° C and are emitting some form of radiant energy, principally in the long-wavelength infrared region. For example, the human body at a temperature of 98.6° F (40° C, 313 K) emits infrared energy from 4000 to 20,000 nm, with the peak output at approximately 9600 nm. Second, most objects must be heated to a temperature of greater than 1000 K (727° C, 1340° F) in order to give off energy at wavelengths short enough to be sensed by the human eye. For example, iron begins to glow red when it is heated to a temperature of about 1200 K, and a typical household tungsten lamp operates at a filament temperature of nearly 3000 K. Both sources will emit large amounts of infrared energy in addition to the visible energy. Third, in order for a solid-object source to emit ultraviolet energy it must be heated to extremely high temperatures. Since tungsten steel melts at 3650 K, incandescent sources are not typically used when large amounts of ultraviolet energy are needed.

Vapor Sources and the Effect of Electrical Discharge

A fundamentally different method for producing light makes use of radiation emitted from gases when an electrical

current is passed through them. Such sources are called *discharge lamps* and generally consist of a glass tube containing an inert gas, with an electrode at each end. An electrical current is passed through the gas to produce light and ultraviolet energy. This energy may be used directly or to excite phosphors coated on the inside of the glass tube, as in a fluorescent lamp.

The basic process involved in producing light is the same for all vapor lamps. The light emission from the vapor is caused by the transition of electrons from one energy state to another. When the electrical current is applied to the lamp, a free electron leaves one of the electrodes at high speed and collides with one of the valence electrons of the vapor atom. The electron from the vapor atom is bumped from its normal energy level to a higher one and exists for a short time in an excited state. After the collision, the free electron is deflected and moves in a new direction at reduced speed. However, it will excite several more electrons before it completes its path through the lamp. The excited electron eventually drops back to its former energy level and, while doing so, emits some electromagnetic radiation.

The radiation emitted may be at any of several wavelengths, depending primarily upon the properties of the vapor in the tube. Each type of vapor atom, when excited, gives off energy at wavelengths determined by its structure. Some gases emit radiation only at a few wavelengths, while others emit energy at many different wavelengths. These sources are said to show a discontinuous or line spectrum. For example, the spectrum of sodium vapor shows a bright yellow line near 600 nm, as shown in Figure 1-8, while mercury vapor produces energy at many different wavelengths,

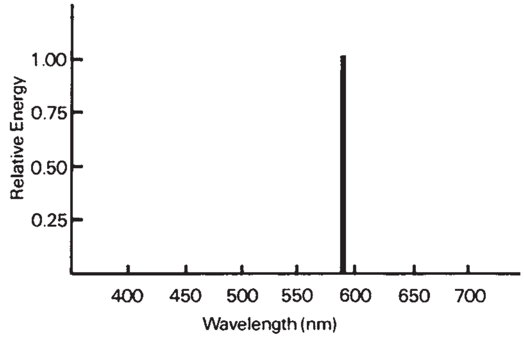

Figure 1-8 Spectral-energy distribution of a low-pressure sodium-vapor source. Such sources appear yellow.

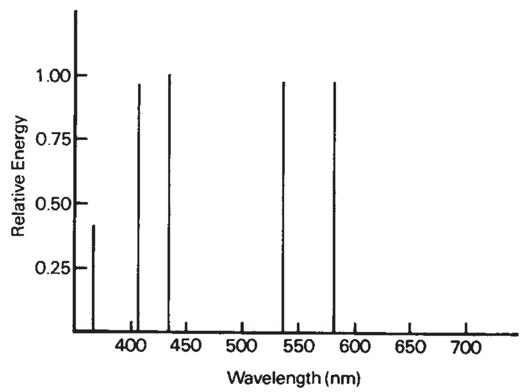

Figure 1-9 Spectral-energy distribution of a low-pressure mercury-vapor source. This source would appear violet.

both in the ultraviolet region and in the visible region, as illustrated in Figure 1-9.

The pressure under which the vapor is dispersed in the tube significantly affects the amount of energy that will be emitted. The terms *low pressure* and *high pressure* are often used to describe such lamps; low pressure indicates some small fraction of atmospheric pressure, while high pressure is applied to sources working above atmospheric pressure. High-pressure sodium-vapor lamps are often used for illuminating streets at night. Low-pressure sodium-vapor lamps are often used as safelights in photographic darkrooms when working with ortho-chromatic materials because they produce light in regions of the spectrum where the emulsion

shows low sensitivity. High-pressure mercury-vapor sources are often used when making blueprints, while low-pressure mercury-vapor sources are used in greenhouses as plant lights because the ultraviolet energy they emit is beneficial to plant growth. It is important to note that the spectral characteristics of the radiation emitted by these sources depends primarily upon the properties of the vapor in the tube.

Perhaps the most commonly encountered vapor source is the fluorescent lamp. These are typically low-pressure mercury-vapor tubes that have phosphors coated on the inside of the glass envelope. When bombarded by the large amount of ultraviolet radiation emitted by the mercury vapor, these phosphors begin to glow and give off visible energy at all wavelengths in the visible spectrum. Thus, the light emitted by a fluorescent lamp is the result of both the discontinuous energy emitted by the vapor and the continuous energy emitted by the fluorescing phosphors.

There are many classes of phosphors that can be used for this purpose, with each phosphor emitting its own color of light. Figure 1-10 illustrates the spectral energy distribution for a typical cool white fluorescent lamp. The light that corresponds to the discontinuous line spectrum produced by the mercury vapor may not be apparent to a human observer because of the ability of the visual system to adapt to variations in the color balance of white light. Photographic films do not have this capability. Therefore, color transparencies made on daylight-type color film with daylight fluorescent illumination tend to have a greenish cast unless an appropriate filter is used.

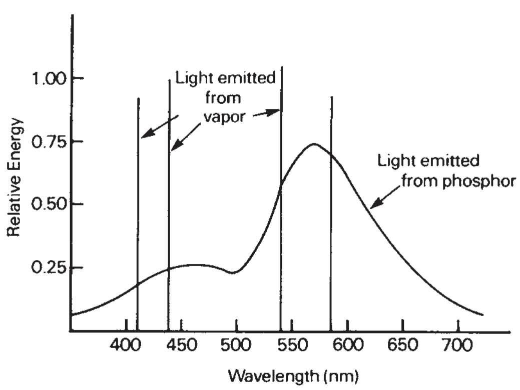

Figure 1-10 Spectral energy distribution of a cool white fluorescent lamp.

Luminescence/ Fluorescence/ Phosphorescence

Luminescence can be described as the emission of light from a substance that has not been heated or light caused by something other than incandescence. Luminescence is a form of cold body radiation, as it usually occurs at low temperatures. It is generally caused by the emission of photons from atoms by exciting them with energy of relatively short wavelengths. As the electrons return to a lower energy level, energy of longer wavelengths is released. The rate at which this occurs can be affected by the presence of an activator, which is made up of ionized atoms that trap, then release the electrons slowly for recombination. The exciting energy is usually in the ultraviolet region, but can be caused by energy in the visible and infrared regions. There are many forms of luminescence.

Chemiluminescence occurs as the result of a chemical reaction and is the emission of light without the emission of heat. A common example of chemiluminescence is found in forensics laboratories that use luminol to test for the presence of blood. The blood glows when it comes in contact with the iron in the luminol. When chemiluminescence happens in a living organism it is

called *bioluminescense*. Bioluminescence is the result of biochemical reactions and is typically seen in fireflies and glowworms. *Galvanoluminescence* is light produced by passing an electrical current through an electrolyte that has a submersed electrode made of an appropriate metal, such as aluminum. When vacuum-tube rectifiers were common, this was the “glow” seen when they were operating. *Triboluminescence* occurs when rubbing breaks the asymmetrical bonds in a crystal, crushing or breaking the material. Examples would be the grinding of sugar with a mortar and pestle or the sparks seen when biting into a Wint-O-Green Life Savers. Solid substances that luminesce are called *phosphors*. Photographers are most concerned with the luminescence that occurs as a result of excitation with ultraviolet energy and light.

Photoluminescence, which include fluorescence and phosphorescence, is caused by a chemical compound absorbing photons, which elevates it to a higher energy state, where the light photons are given off until the compound returns to its original energy state. The length of time this takes is typically around 10 nanoseconds.

Fluorescence is luminescent emission of electromagnetic radiation in the visible region that occurs during the time of excitation. Thus, phosphors that are radiated with ultraviolet energy fluoresce. When the excitation is stopped, the fluorescence ceases within about 10^{-8} seconds, but it sometimes continues for as long as 10^{-1} seconds, depending on the activator.

Phosphorescence is the emission occurring after the excitation has been stopped, and which continues for somewhat longer than 10^{-8} seconds up to several hours. The duration strongly depends on temperature. Phosphorescence is similar to fluorescence, but has a slower rate of decay. A common example of phosphorescence is glow-in-the- dark toys for children.

Some dyes fluoresce, including fluorescein, eosin, rhodamine, and a series of dyes (and other materials) that are used as brighteners in substances such as paper and cloth. Photographic papers may contain brighteners to give them cleaner and more brilliant whites. Most modern papers are treated with brighteners, a distinguishing characteristic when comparing modern prints to those made thirty or forty years ago, without brighteners. The occurrence of brighteners in fabrics and similar materials can present problems in color photography when the ultraviolet component of electronic flash energy (or other light sources) causes them to fluoresce, most often in the blue region of the spectrum. This has a strong effect on the reproduced color of the material, often rendering it blue or cyan when the other materials in the scene have been reproduced satisfactorily in the photograph. The effect is minimized or eliminated by the use of an ultraviolet-absorbing filter over the electronic flash, or other source, to prevent it from exciting the fluorescing dyes or pigments in the material. An ultraviolet filter over the camera lens in this case would not correct for the fluorescence.

Brighteners in photographic papers fluoresce to produce whiter whites.

Brighteners in clothing, paper products, hair rinses, etc., can adversely affect the color of the objects in color photographs.

Fluorescent lamps excite gas molecules within the tube by means of electrons, to produce energy of discrete wavelengths, or lines, largely in the blue and ultraviolet regions (but this depends to a great extent on the gas elements in the tube). Some of this energy is absorbed by phosphors coated on the inside of the tube and is converted to longer-wavelength (visible) radiation. The color of the fluorescent emission is highly dependent on

As color temperature increases, the color balance of the light shifts from reddish to bluish.

Tungsten color film can be used in daylight by using a filter that converts daylight to tungsten-quality light.

An orange 85B filter converts daylight to tungsten quality. A bluish 80A filter converts tungsten light to daylight quality.

the phosphor material, and the activators incorporated in it.

Fluorescing screens are used extensively in radiography. In this application, they are called *intensifying screens*. They fluoresce when activated by the X-rays used for exposure, and the visible radiation from the screens is considerably more effective in exposing photographic emulsions than the X-rays themselves. The screens are placed in contact with both sides of the film, in the film holder, during exposure.

The Use of Color Temperature

Because the amount and color of radiation emitted by a solid-object source is very much temperature-dependent, the color of light being emitted from such a source can be completely specified by the Kelvin temperature (K) at which it is operating. Such a rating is referred to as the *color temperature* of the source. A color temperature may be assigned to any light source by matching it visually to a blackbody radiator. The temperature of the blackbody radiator is raised until the color of its light visually matches that from the lamp, and the Kelvin temperature of the blackbody is then assigned as the color temperature of the lamp. Thus, the use of color temperature ratings in photography presumes that the lamp being described adheres to the same heat-to-light relationship as does the blackbody radiator, meaning the plot of their spectral power distributions are continuous as is the blackbody radiation in Figure 1-7. For incandescent lamps, this presumption is correct. However, the color of light emitted by some sources, such as fluorescent lamps, has no relationship to the operating temperature. (See Figures 1-8 and 1-9.) In these cases, the term *correlated color temperature* (CCT) is used to indicate that the color of light emitted by a blackbody radiator of that temperature produces the closest visual match that can be made with the source in question. It is important to note here that a visual match of two sources does not ensure a photographic match. In fact, in most cases the photographic results will be different.

The color temperatures of a variety of light sources are given in Table 1-2. It is apparent that photographers are faced with a tremendous range of color temperatures, from the yellowish color of a candle at about 1800 K to the bluish appearance of north sky light, rated at 15,000 K. Notice that as color temperature increases, the color of light emitted from the source shifts from red to white to blue in appearance. For photographers to produce excellent photographs under widely varying illuminant conditions, color films are designed for use with different color temperatures, such as tungsten or daylight. The actual color temperature encountered from a lamp in practice can vary significantly as a result of reflector and diffuser characteristics, changes in the

Table 1-2 The color temperatures of some common light sources

Source	Color Temperature °K	Mired Value
Candle	1800–1900	555–526
Tungsten lamp	2800	357
CIE Tungsten illuminant or Illuminant A	2856	350
250-watt photographic lamp	3200	312
250-watt studio flood lamp	3400	294
CIE Cool White Fluorescent	4100	244
Direct sunlight	4500	222
CIE D50 or horizon light	5000	200
Electronic flash	5500–6000	182–166
CIE D65 of noon daylight	6500	154
Sky light (overcast sky)	8000	125
North sky light	15,000 (approximately)	67

power supply, and the age of the bulb. Consequently, it is often necessary to measure the color temperature of the source with a color-temperature meter when using color films.

Modern color-temperature meters typically use three silicon photodiodes that are filtered for the red, green and blue sensitivities that approximate the sensitivity of color film. The meter will measure the amount of energy present in the three regions and determine the color temperature by finding the closest match to a blackbody curve. Meters will either provide a color temperature, a mired shift, or a Wratten filter number to achieve the desired color temperature. These meters are intended to be used with continuous spectral power distribution. However, when used with vapor sources that produce a discontinuous spectral power distribution, the results may be very misleading because of significant differences in the measured response compared to the blackbody curves.

When the color temperature of the light from a solid-object source does not match the response of the film, light-balancing filters must be used over the camera lens. If the color temperature is too high, a yellow filter over the camera lens will lower the color temperature of the light that the film receives. If the color temperature of the light is too low, a blue filter can be used to raise it. If the filters are desaturated in color, then the changes to color temperature will be relatively small, whereas saturated filters will give large changes in color temperature.

The filters necessary to properly correct the color of light from vapor sources, such as fluorescent lamps, must either be determined from the manufacturer's literature or from tests performed with the color film itself.

When the color temperature of the light does not match the response of the camera's digital sensor, the photographer has several options. Most digital SLR cameras have several built-in white balance settings that correspond to specific color temperatures, such as sunny daylight, cloudy daylight, indoor incandescent, or indoor fluorescent. The photographer can choose the white balance setting that corresponds to the situation. This may or may not give satisfactory results. Consider indoor incandescent light. The published color temperature for an incandescent bulb in my living room is 2850 K and the incandescent setting on my camera is calibrated to 3000 K. This discrepancy may cause a color cast in the image. The second option that is available on many digital cameras is a custom white balance setting. The camera is aimed at an object in the scene that is white, and this is selected as the white balance for the image. Done correctly, this method will produce excellent results. The third option is to capture the image in raw format and color-correct the image later using editing software.

A mired is defined as 10^6/K.

A mired shift is the mired value difference between two light sources.

A Wratten filter number is the common labeling system used for optical filters in photography.

The Mired Scale

Although color temperature provides a useful scale for classifying the light from continuous-spectrum sources, it does have some limitations. For example, a 500 K change at the 3000 K level does not produce the same visual or photographic effect as a 500 K change at the 7000 K level. This is because there is a nonlinear relationship between changes in a source's color temperature and the changes in the color of light it produces, which is illustrated in Figure 1-11.

10 Mireds = 1 Decamired.

Mired is an acronym for the term micro-reciprocal-degrees.

This awkwardness can be eliminated through use of the mired value. The *mired value* is the reciprocal

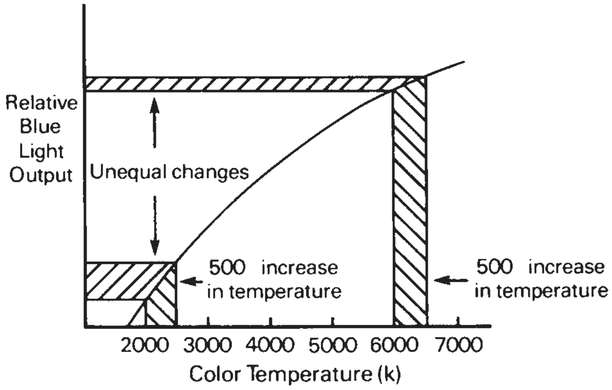

Figure 1-11 The relationship between color temperature and the relative amount of blue light being given off by a solid-object source.

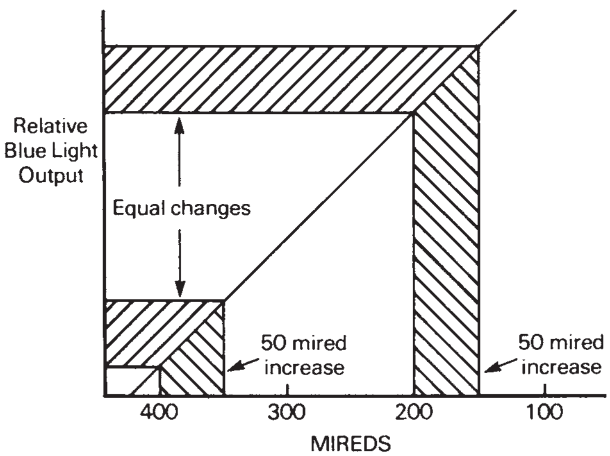

Figure 1-12 The relationship between mireds and the relative amount of blue light given off by a solid-object source.

of the color temperature and has a nearly linear relationship existing between this value and the effect. The reciprocal of color temperature would be quite small, so it is commonly multiplied by 1 million to obtain a number of an appropriate size. Therefore, to convert color temperatures to the mired scale, the following formula is used:

$$\text{Mired Value} = \frac{1}{\text{Color Temperature}} \times 10^6$$

$$\text{or } \frac{1{,}000{,}000}{\text{Color Temperature}} \tag{Eq. 1-2}$$

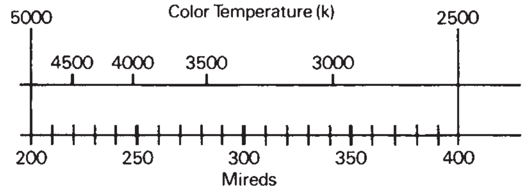

Figure 1-13 Comparison of color temperature and mired scale.

The term *decamireds* is sometimes used for convenience; each decamired contains 10 mireds. For example, the mired value for a color temperature of 12,5000 K is 80 mireds or 8 decamireds.

Figure 1-12 illustrates the relationship between changes on the mired scale and changes in the resulting effect. It shows that equal changes in the mired scale produce equal changes in the effect. The relationship between color temperature and mireds is illustrated in Figure 1-13, which indicates that the higher the color temperature, the lower the mired value. Consequently, bluish sources with very high color temperatures will have very low mired values, while reddish-appearing sources with low color temperatures will have high mired values.

The mired scale is most frequently used for color-compensating filters that are intended to correct the color of light from a source to match the response of color film. These filters are given a mired shift value (MSV). This value indicates the change in the color of the light that will result when using that filter. Bluish filters that are used to lower color temperature are given negative values while amber or yellow filters that raise color temperature are given positive values.

The equation used to determine the mired shift required, and hence the filters needed, to correct the color temperature of one light source (CT_1)

to the color temperature of a second light source (CT_2) is:

$$MSV = \left(\frac{1}{CT_2} - \frac{1}{CT_1} \right) \times 10^6 \quad \text{(Eq. 1-3)}$$

For example, if it is desired to expose a daylight color film balanced for 5500 K with a tungsten lamp operating at 3000 K, a color correction filter will be necessary to obtain the proper color balance. The color temperatures are converted to mired values using Eq. 1-3, as shown below:

$$MSV = \left(\frac{1}{5500} - \frac{1}{3000} \right) \times 10^6 = -151$$

Thus, to correct this light source, a filter providing a mired shift of −151 would have to be used over the camera lens. The filter manufacturer's data sheet will provide the information necessary to determine the appropriate filter for this mired shift value. A major benefit of using the mired scale for designating filters is that a given mired change will have the same effect on the color of the light from solid-object sources at any color temperature.

The color-temperature meters discussed previously often read out directly in mired values, and the mired shift can be calculated from that.

Color-Rendering Index

Correlated color-temperature (CCT) specifications work quite well for describing the visual appearance of vapor and fluorescent sources. However, when considering the way an object's color appears under a specific light source, CCTs are often misleading. A *color rendering index* (CRI) was developed by the CIE to evaluate a light source's ability to accurately reproduce the perceived color of an object when compared to a standard light source. For light sources with a color temperature between 2000 and 5000 K, the standard is the blackbody radiator. For sources above 5000 K, the standard is D65.

A CRI value of 100 means there is no color difference between the light source being evaluated and the standard light source. By definition, a tungsten or incandescent light source has a CRI near 100, as the CRI was designed to evaluate continuous spectrum sources.

Since fluorescent lamps do not follow the energy-emission properties of a blackbody radiator, CCTs do not indicate the amount of energy being produced at each wavelength. For example, the spectral energy distributions for two fluorescent lamps of equal correlated color temperature (4200 K) are shown in Figure 1-14. Note that the lamp labeled Cool White Deluxe is producing more red light than the lamp labeled Cool White, which would result in widely different color rendering for some objects. For example, if a person's face were illuminated

Daylight has a higher color temperature than tungsten light—and a lower mired value.

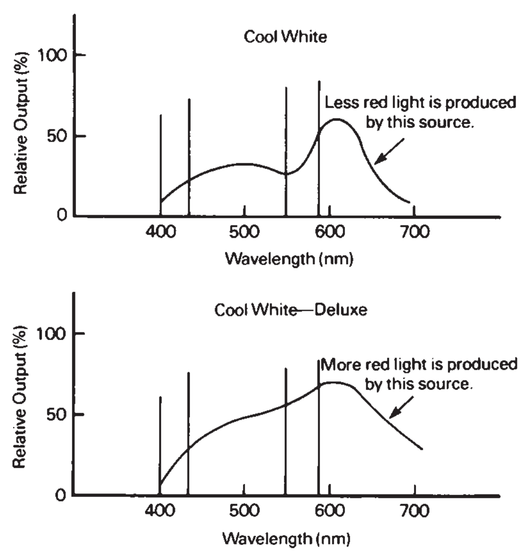

Figure 1-14 Spectral-energy distributions for two fluorescent lamps with same correlated color temperature (4200 K).

The Munsell color system is a color space that specifies color based on their hue, value, and chroma.

by these sources, the Cool White Deluxe lamp would provide more red light, resulting in a healthier, more natural skin-complexion appearance than that given by the Cool White lamp.

Determining the color rendering index, *R*, for any given light source requires that the spectral energy distribution and the correlated color temperature are known, so that an appropriate reference source can be selected. In this method, eight arbitrary Munsell color samples are used, and the CIE chromaticities under the given source are calculated. A similar set of calculations under the selected reference source will give eight different CIE chromaticities. The differences between the two sets of data indicate the color shift of the given light source in relation to the reference source. The eight differences are then averaged to arrive at the color-rendering index, *R*.

The *R* value is based upon an arbitrary scale that places a specific warm white fluorescent lamp with a correlated color temperature of 3000 K at $R = 50$ and the reference source at $R = 100$. The reference source always has an *R* equal to 100. Thus, the higher the *R* value for a given source, the more closely object colors will appear to their counterparts under the reference source, and, therefore, the better the color rendition. The color rendering indexes for a variety of fluorescent lamps are given in Table 1-3.

Table 1-3 The correlated color temperatures and color rendering indexes for a variety of fluorescent lamps

Lamp Name	Correlated Color Temperature	Color Rendering Index
Warm white	3000 K	$R = 53$
Warm white—deluxe	2900 K	$R = 75$
White	3500 K	$R = 60$
Cool white	4200 K	$R = 66$
Cool white—deluxe	4200 K	$R = 90$
Daylight	7000 K	$R = 80$

Some limitations to this concept should be noted. First, since the calculated *R* value is obtained in relation to a reference source, two given sources can only be compared to each other if their reference sources are similar (within approximately 200 K). Second, since the *R* value is an average taken from eight different colors, it does not specify the performance of the source on a specific color. Third, the *R* value is based upon the visual appearance of the object colors and not their photographic appearance. Thus, a source can have a high *R* value (90 or greater) and not give desirable color reproduction in a color photograph.

The Polarization of Light

As discussed previously, light, like other forms of radiation in the electromagnetic spectrum, is believed to move in a wave motion. The vibrations of these waves occur in all directions at right angles to the path of travel, as illustrated by the light beam to the left of the filter in Figure 1-15. This is described as an *unpolarized* light beam. However, the wave can be made to vibrate in one direction only, and when this occurs, the light is said to be *polarized*. The light beam on the right of the filter in Figure 1-15 illustrates this condition. Such polarization of light occurs naturally in a number of ways described below.

1. Light emitted from a portion of clear blue sky, at right angles to a line connecting the viewer (or camera) and the sun, is highly polarized. The scattering of the light rays is caused

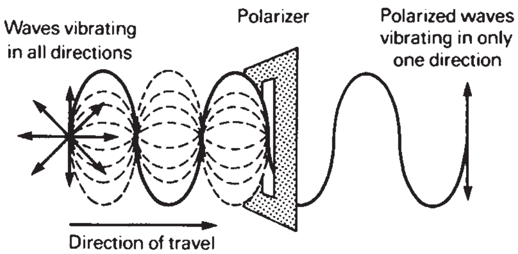

Figure 1-15 The polarization of light.

by very small particles in the atmosphere such as dust and molecules of water vapor and other gases. As the angle decreases, the effect also decreases, as illustrated in Figure 1-16. Thus, a portion of the light blue sky encountered in typical outdoor scenes is polarized.

2. Light becomes polarized when it is reflected from a flat, glossy, nonmetallic surface, such as glass, water, and shiny plastics. This effect is maximized at an angle whose tangent is equal to the refractive index of the reflecting material; this is known as the *Brewster angle*. For common surfaces, such as glass and water, this angle is approximately 55° from the perpendicular (35° from the surface) and is illustrated in Figure 1-17.
3. Light becomes polarized when it is transmitted through certain natural crystals or commercially manufactured polarizing filters. Among the substances having the ability to polarize light are the dichroic crystals, particularly the mineral tourmaline. When a beam of unpolarized light passes through a thin slab of tourmaline, it becomes polarized. This property can be demonstrated by rotating a second slab of tourmaline across the direction of polarization, as illustrated in Figure 1-18. When the second slab is rotated to a position of 90° from that of the first, no light will be transmitted through the second filter. Commercially available polarizing filters are made from dicrylic substances whose chemical composition calls for the grouping of parallel molecular chains within the filter. This is the nature of the filters illustrated in Figures 1-15 through 1-19.

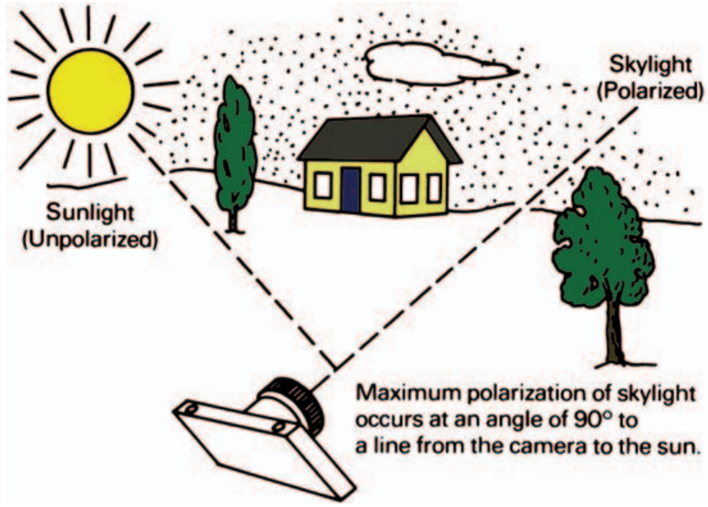

Figure 1-16 The polarization of sky light.

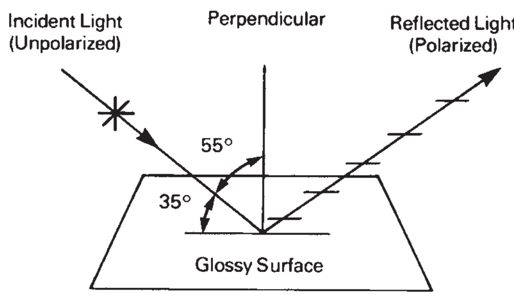

Figure 1-17 The polarization of light reflected from a glossy surface.

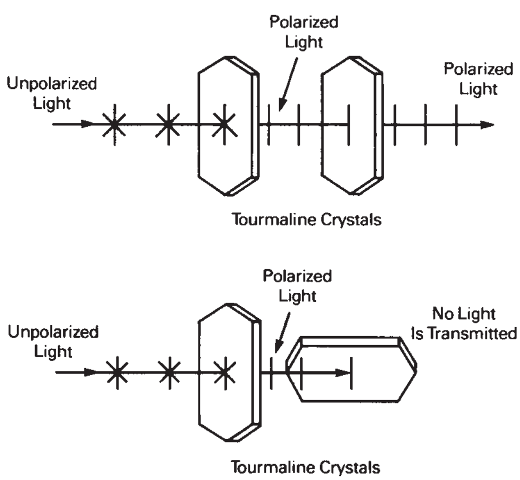

Figure 1-18 The polarizing effect of a tourmaline crystal.

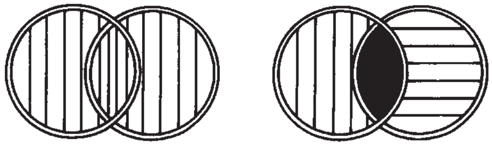

Figure 1-19 The use of polarizing filters to control light.

Figure 1-20 A polarizing filter was used to take the photograph on the right. The sky is significantly darker. (Photographs provided by Professor Stephen J. Diehl, Rochester Institute of Technology)

Figure 1-21 A polarizing filter was used to take the photograph on the right. The colors in the image are more saturated by removing glare with a polarizing filter . (Photographs provided by Professor Stephen J. Diehl, Rochester Institute of Technology)

Polarized light will become depolarized when it strikes a scattering medium. This most frequently occurs when the light is reflected from a matte surface, such as a sheet of white blotting paper. It can also be depolarized upon transmission through a translucent material, such as a sheet of matte acetate.

The phenomenon of polarized light provides the photographer with a very useful tool for controlling light. For example, a polarizing filter will absorb light that is in one plane of polarization. If the plane of polarization of the filter and the plane of polarization of the light are the same, the maximum amount of light will be transmitted. However, if they are at right angles to each other, no light will pass, as shown in Figure 1-19. At angles between these two, varying amounts of light will be transmitted, allowing for the useful control of light. Thus, polarizing filters can be thought of as variable neutral density filters. Figure 1-20 illustrates the effect that a polarizing filter has on blue sky. The effect on the sky can be dramatic as shown. Figure 1-21 shows the use of a polarizing filter to reduce the glare off the tree and dramatically enhance the colors in the image.

Practical Sources of Light and their Properties

Thus far, the discussion of light has centered on methods of production, properties, and measurement. At this point, we will consider some practical sources of light commonly encountered by the photographer.

Daylight

Daylight is usually composed of at least two different sources of light: (1)

direct sunlight, which is modulated by the earth's atmosphere, and (2) blue sky light, which is the light reflected from the atmosphere. Additional light may also reach the subject by reflection from objects. The nature of daylight at any given time depends upon the geographical location, the season of the year, the time of day, the current weather conditions, and the surroundings. When the sky is clear, the amount of direct sunlight is at a maximum, which is about 88% of the total light on the ground, producing a lighting ratio of approximately 8:1. The ratio decreases as the amount of overcast increases.

The high temperature of the sun produces sunlight, and its energy distribution outside the earth's atmosphere closely approximates that of a blackbody source at 6500 K. In passing through the earth's atmosphere, a considerable amount of this light is lost, particularly in the blue region, and the color temperature of the sunlight plus the skylight varies between 5000 and 6000 K on the ground during the middle of the day. Daylight-type color films are balanced for a color temperature of 5500 K. Variations in color temperature with the time of day are illustrated in Figures 1-22 and 1-23. Color-compensating filters can be used on the camera lens when the color temperature of the daylight does not match that for which color film was manufactured or custom white balancing can be used for digital cameras. The use of color temperature to describe the appearance of daylight is not completely appropriate, however, since the energy-output characteristics of daylight only approximate those of a blackbody radiator.

Skylight is blue because the small particles in the atmosphere selectively scatter light, especially the short wavelengths, away from the direction of travel of the sunlight and toward the observers below. This effect is known as *Rayleigh scattering*, and varies inversely with the fourth power of the wavelength. Thus the scattering at 400 nm is 9.4 times that at 700 nm. The color temperature of blue skylight ranges between 10,000 and 20,000 K.

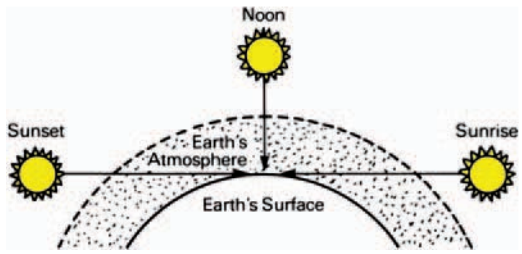

Figure 1-22 The relationship between position of the sun and the length of the sunlight's path of travel through the earth's atmosphere.

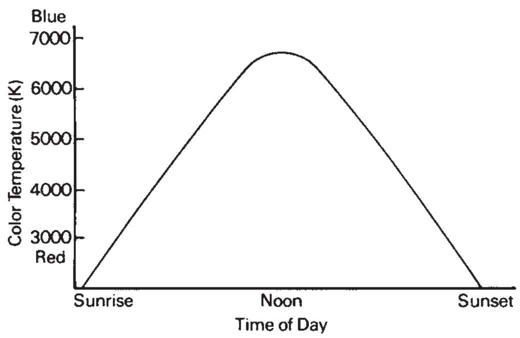

Figure 1-23 The variation in color temperature of light with time of day at the surface of the earth (no cloud cover).

Tungsten-Filament Lamps

Incandescent lamps emit light when the tungsten-filament wire reaches a high temperature as the result of its resistance to the passage of electricity—thus, electricity is converted to heat which is converted to light. The upper temperature limit for this type of source is 3650 K, the melting temperature of tungsten. Color temperature is an appropriate measure of the color quality of the light emitted by tungsten-filament lamps, and it

The color temperature of daylight is considered to be 5500 K.

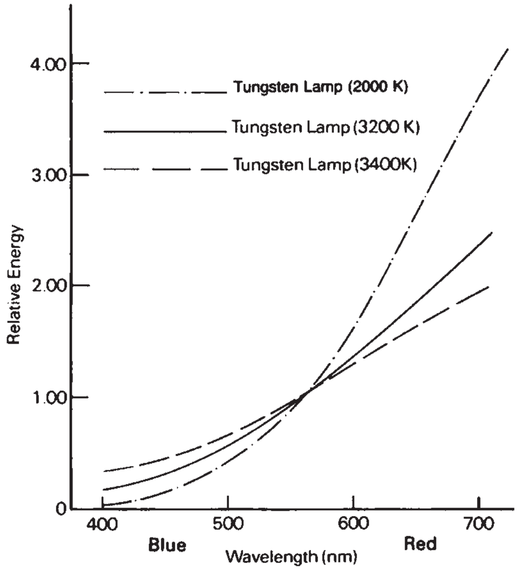

Figure 1-24 Relative spectral-energy distributions for three incandescent sources.

Heating a tungsten filament to the temperature required to produce daylight-quality light would cause the filament to melt.

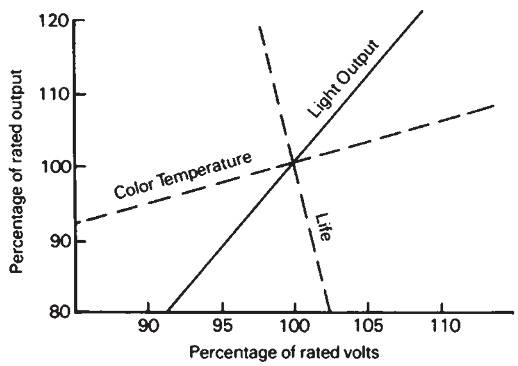

Figure 1-25 The variation in light output, color temperature, and life of a tungsten lamp at different voltages.

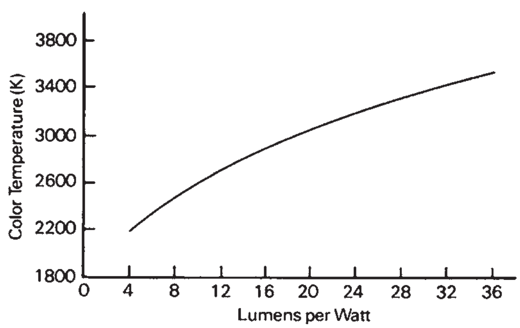

Figure 1-26 The average relationship between luminous efficiency and color temperature of tungsten filament lamps.

5000 K fluorescent lamps are recommended for transparency illuminators and print viewers.

ranges from approximately 2700 K for 15-watt household lightbulbs to 3400 K for photoflood lamps, which have a relatively short life of 10 hours or less.

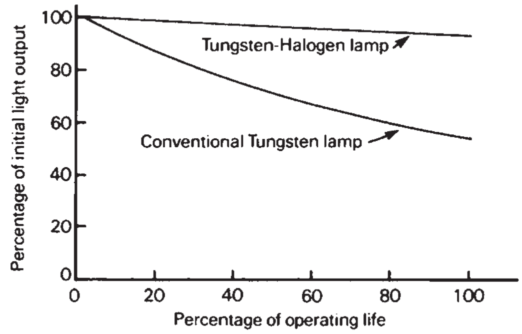

Figure 1-27 Typical lamp depreciation for a conventional tungsten lamp and a tungsten-halogen lamp.

Photographic studio lamps rated at 3200 K have approximately 10 times the life expectancy since lamp life depends primarily upon the rate at which tungsten evaporates from the filament, which in turn varies with the temperature. (See Figures 1-24, 1-25, and 1-26.)

Tungsten-Halogen Lamps

Tungsten-halogen lamps, sometimes referred to as quartz-iodine lamps, differ from conventional tungsten lamps in that iodine is added to the gas in the tube and the envelope is made from quartz or other high-temperature glass. The iodine combines with the tungsten that evaporates from the filament, but the high temperature of the filament produces a decomposition that re-deposits tungsten on the filament, thereby increasing the life of the filament and preventing the deposit of tungsten on the envelope. Figure 1-27 illustrates the loss in total light output for conventional tungsten lamps and tungsten-halogen lamps during their operating lives.

Fluorescent Lamps

Fluorescent lamps produce light by establishing an arc between two electrodes in an atmosphere of very low-pressure mercury vapor contained in a

glass tube. This low-pressure discharge produces ultraviolet radiation at specific wavelengths that excite crystals of phosphors lining the wall of the tube. Phosphors such as calcium tungstate have the ability to absorb ultraviolet energy and to re-radiate this energy as light. The color of light emitted by a fluorescent tube depends largely on the mixture of fluorescent materials used in the phosphor coating.

The light that reaches the eye or camera from such a lamp, therefore, consists of the light given off by these fluorescent compounds plus such part of the light from the mercury vapor that gets through them without being absorbed. The result is a continuous spectrum produced by the fluorescent material, superimposed upon the line spectrum of energy produced through the electrical discharge of the mercury vapor. The spectral-energy distributions for three of the more commonly encountered fluorescent lamps are illustrated in Figure 1-28.

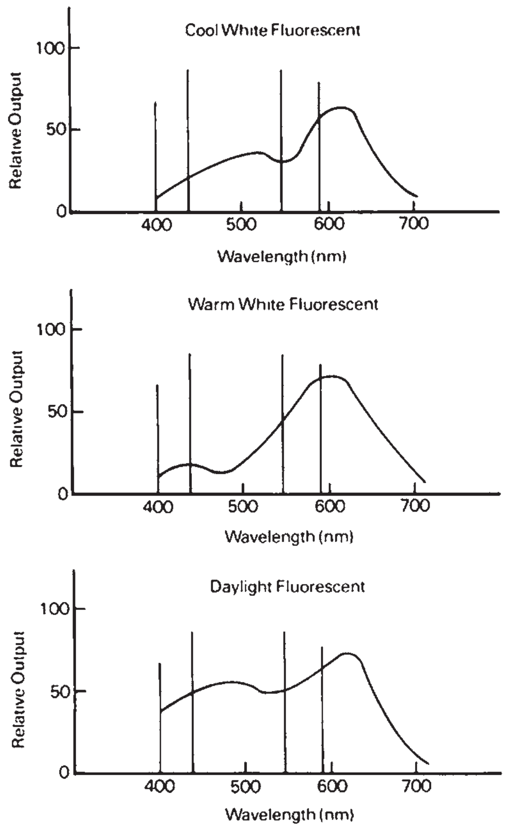

Figure 1-28 Spectral-energy distributions of three different fluorescent lamps.

Fluorescent lamps with a correlated color temperature of 5000 K (such as the General Electric Chroma 50®) are believed to give a better match to daylight and are now specified in ANSI standards for transparency illuminators and viewers. Fluorescent lamps find widespread use because they generate very little heat and are less expensive to operate (that is, they have higher luminous efficiency) than tungsten lamps. Additionally, they are low luminance sources, because they possess larger surface areas than do tungsten lamps. The result is that these lamps have less glare and produce more diffuse illumination. Fluorescent lamps are nearly always used for commercial lighting and, consequently, photographers working under such light conditions should be familiar with their characteristics.

The luminous efficiency of fluorescent lamps is generally higher than that of tungsten sources, ranging between 40 and 60 lumens/watt, making them more economical to operate. Additionally, the average life of a fluorescent lamp is approximately 5,000 hours, which is nearly five times longer than that of a conventional tungsten lamp.

Luminous efficacy is a property of a light source that indicates the portion of the emitted electromagnetic radiation that is usable for human vision.

High-Intensity Discharge Lamps

Similar in operation to fluorescent lamps, high-intensity discharge lamps produce light by passing an arc between two electrodes that are only a few inches apart. The electrodes are located in opposite ends of a small sealed transparent or translucent tube.

Camera filtration is recommended when making color photographs with discharge-lamp light sources.

Also contained within the tube is a chemical atmosphere of sodium and/or mercury. The arc of electricity spanning the gap between the electrodes generates heat and pressure much greater than in fluorescent lamps, and for this reason these lamps are also referred to as high-pressure discharge sources. The heat and pressure thus generated are great enough to vaporize the atoms of the various metallic elements contained in the tube. This vaporization causes the atoms to emit electromagnetic energy in the visible region. Since the physical size of the tube is small, it allows for the construction of optical sources that have excellent beam control. Such sources are frequently employed for nighttime illumination of sports stadiums, highways, exteriors of buildings, and the interiors of large industrial facilities.

As in the operation of low-pressure discharge sources (i.e., fluorescent lamps), high-intensity discharge lamps produce spikes of energy at specific wavelengths. These peaks are the result of specific jumps of the electrons within the atomic structure of the metallic elements. Energy is emitted in peaks located in different positions of the visible spectrum for each element. Thus these lamps do not have a true color temperature, since they are not temperature dependent for the color of light emitted. The three most commonly encountered high-intensity discharge sources are mercury, metal halide, and sodium. (See Figures 1-29, 1-30, and 1-31.)

Since their introduction in the 1950s, high-intensity discharge sources have steadily increased in use. Mercury-vapor lamps were the first lamps of this type available. Although their efficiency was high (17 to 46 lm/W) compared to tungsten, their color-rendering ability was poor. Today, the metal halide (54 to 92 lm/W) and sodium lamps (59 to 106 lm/W) are preferred for both efficiency and improved color rendering. However, these sources pose the same problems photographically as do fluorescent lamps. The use of color temperature and the mired scale is entirely

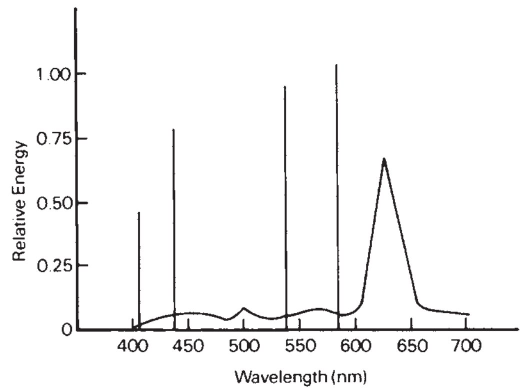

Figure 1-29 Spectral-energy distribution of a high-intensity mercury discharge source with the name DeLuxe White®.

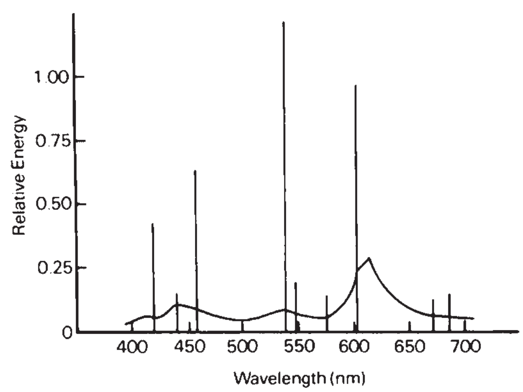

Figure 1-30 Spectral-energy distribution of a high-intensity metal halide discharge source, the General Electric Multi-Vapor® lamp.

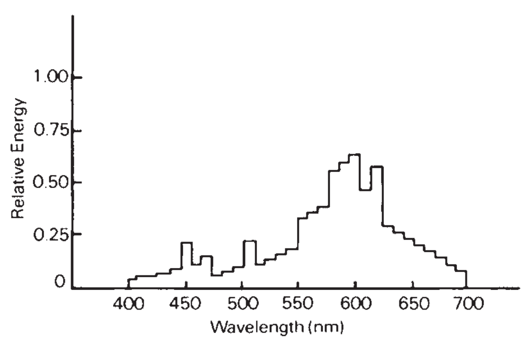

Figure 1-31 Spectral-energy distribution of a high-intensity sodium-vapor discharge source, the General Electric Lucalox®.

inappropriate for these sources. When using films under these sources, the user will have to experiment to find the proper filtration. Digital cameras have proven to be easier to use to manage these issues, as custom white balance settings will take care of this problem.

Electronic Flash

An *electronic-flash* lamp consists of a glass or quartz tube that is filled with an inert gas such as xenon and has electrodes placed at either end. When a high-voltage current from the discharge of a capacitor passes between the electrodes, the gases glow, producing a brilliant flash of light. The total time of operation is exceedingly short, with the longest times being on the order of 1/500th second and the shortest times approaching 1/100,000th second. The time-light curve for a typical electronic flash unit is shown in Figure 1-32. The effective flash duration is typically measured between one-third peak power points, and the area contained under the curve between these limits represents nearly 90% of the total light produced. If this number is measured in lumen seconds, the light being emitted in all directions is considered. A more revealing measurement is the number of effective beam-candle-power seconds, which is a measurement of the light output at the beam position of the lamp.

The spectral-energy distribution of these sources shows a line spectrum, the exact nature of which is determined by the type of gas dispersed in the tube. Although the gas gives a line spectrum, there are so many lines and they are so well distributed throughout the visible spectrum that no serious error is involved in considering the spectrum to be continuous, as shown in Figure 1-33. The spectrum from the

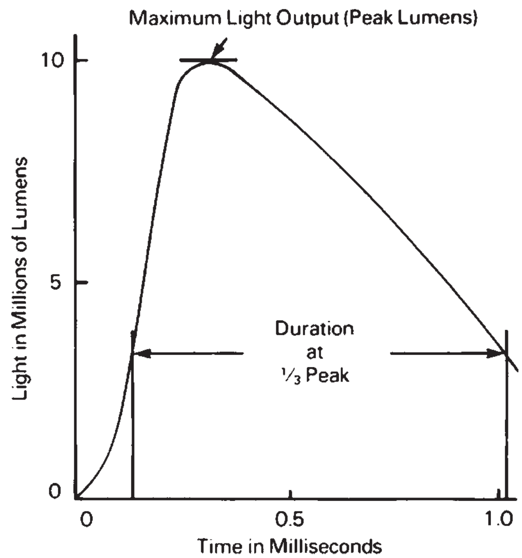

Figure 1-32 Light output curve of an electronic flash unit.

The color temperature of most electronic-flash units is close to that of photographic daylight.

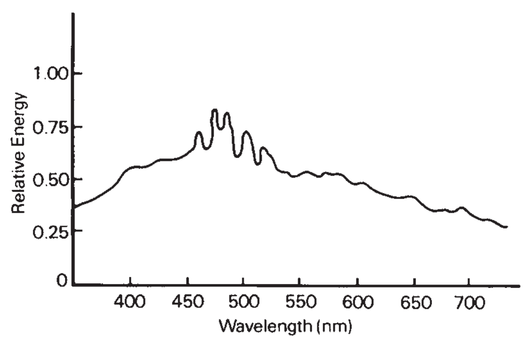

Figure 1-33 Relative spectral-energy distribution of a typical xenon-filled electronic flash unit.

gas in these tubes approaches incandescence because of the high-current density at the time of discharge. The resulting light has a correlated color temperature of approximately 6000 K, which is conveniently close to the 5500 K level at which daylight color films are designed to operate. A color-correction filter built into the lens of the flash unit often compensates for the small difference in color temperature. If no such filter exists in the source, a color-correction filter can be used over the camera lens to avoid a bluish cast in the color images.

The total light output for an electronic-flash unit depends upon the

design of the flash lamp and reflector, the voltage, and the capacity of the capacitor. In the early days of electronic flash photography, the exposure was controlled by setting the *f*-number at the number obtained by dividing a guide number by the flash-to-subject distance. Electronic flash meters are now commonly used, and many portable electronic flash units have built-in sensors that monitor the light reflected from the subject and quench the flash when sufficient light falls on the subject to produce the desired exposure effect.

Electronic flash units have proven to be a most useful source of light for photographers. Their consistency in color output, quantity of light output from flash to flash, and the extremely short duration of the flash are all reasons for the widespread use of these sources.

Lasers

***Laser* is an acronym for Light Amplification by Stimulated Emission of Radiation.**

The word *laser* is an acronym for *light amplification by stimulated emission of radiation*. A laser is an electronic-optical device that produces coherent radiation. Hughes Research Laboratories demonstrated the first operational laser in May of 1960. Since then lasers have grown to become a multibillion-dollar industry with applications in optical storage devices such as compact disc and DVD players, scanners for bar code readers, laser pointers, metal cutting, and inscribing patterns such as letters on computer keyboards. There are also medical applications such as laser eye surgery and in the science for spectroscopy and other applications.

A laser will emit light in a monochromatic (a single wavelength) narrow low-divergence beam. Lasers consist of gain medium inside an optical cavity that can receive an energy supply to the gain medium. The gain medium is a material such as a gas, liquid, solid, or free electrons that are of the required optical property. The simplest design of the cavity will consist of two mirrors arranged so the light will bounce back and forth passing through the gain medium each time. For light to be emitted from the laser one of the mirrors is partially transparent.

When the light travels though the gain medium its power is increased or amplified. This is a process by which a photon of light stimulates an excited atom to emit a second photon that is at the same frequency and moves in the same direction as the initiating wave. This concept is sometimes referred to as optical pumping, which is the process whereby matter is raised from a lower to a higher energy state.

For example, the potential energy of water is raised when it is pumped from an underground well to a storage tank on top of a tower. There are many forms of matter that can be elevated or pumped, from one energy level to a higher one, by optical methods. The atoms of some substances will absorb photons of light and when doing so increase their energy level. These excited atoms do not remain in the higher energy state but fall randomly and spontaneously to their lower or ground state. When this occurs, the stimulated atom emits a photon of light. Therefore, the gain medium amplifies the light waves by means of the stimulated emission process. Energy must be pumped into the laser medium to make it active. One way to supply this pumped energy is with light from an external source such as a flash tube.

Figure 1-34 illustrates the basic properties of a ruby laser. A ruby crystal rod has parallel polished ends which are mirrored surfaces. One end is only

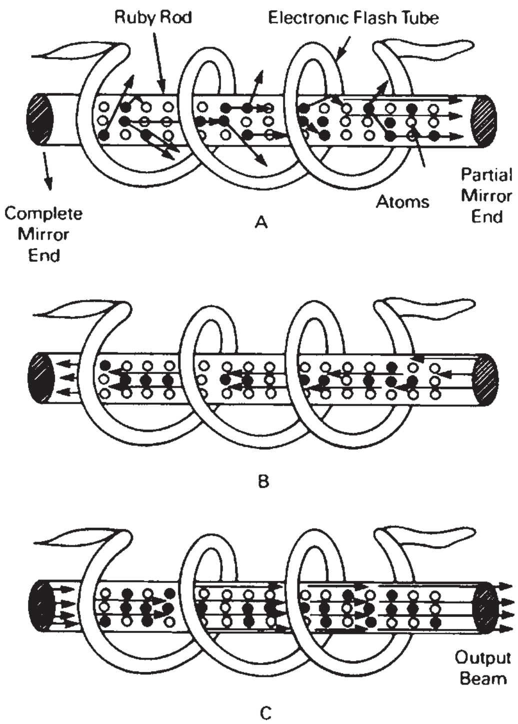

Figure 1-34 Basic operation of a ruby laser (the principle of "optical pumping").

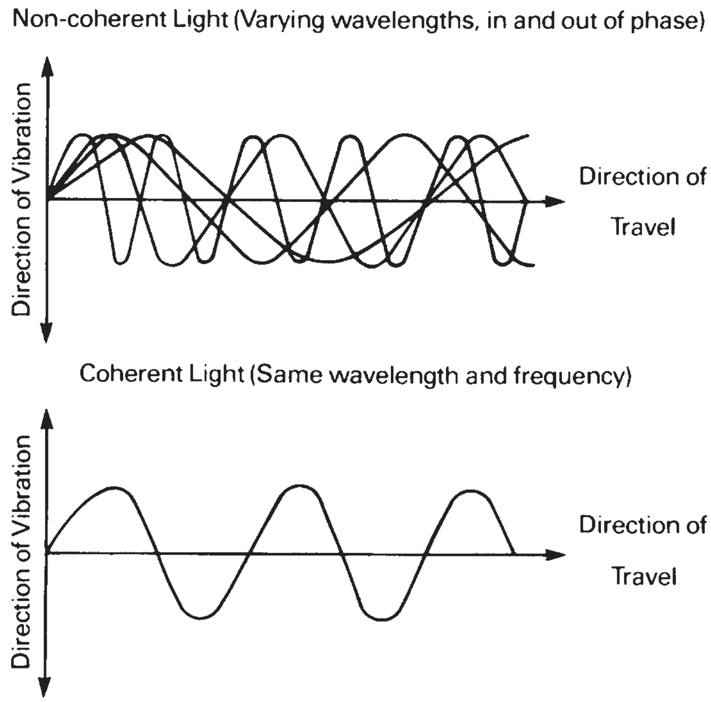

Figure 1-35 Non-coherent and coherent light waves.

partially silvered and acts as a window for the light to escape. Energy is supplied to the ruby crystal by a powerful electronic flash tube, which serves to pump the atoms of the crystal to a higher energy state. They exist at this level for a few millionths of a second before dropping to their ground level, resulting in the emission of a photon of light as shown in Figure 1-34A. Although many of these photons will pass out of the crystal walls and be lost, eventually one photon will move directly along the rod and be reflected from the polished ends, passing back and forth along the rod until it encounters an atom in the excited elevated state, as shown in Figure 1-34B. As it strikes this excited mirrored atom, the atom radiates its photon in exact phase with the photon that struck it. This second photon will, in turn, stimulate another atom and, in this cascade process, continue to fill the rod with in-phase radiation that is oscillating back and forth between the mirrored ends of the rod. A portion of this radiation is emitted through the partially silvered end of the rod and becomes the laser beam (see Figure 1-34C).

The entire process occurs within a few thousandths of a second, and as the flash tube fires again, the process repeats itself. The result is an intense monochromatic beam of light that can be focused to a tiny spot. Lasers emit light waves that are in phase with each other, and are described as being coherent. Conventional light sources radiate light of varying wavelengths in and out of phase with each other, which is described as non-coherent light. This concept is illustrated in Figure 1-35. It is this high degree of coherence that makes laser light different from that of all other sources.

The Language of Light

The intelligent selection and application of light sources require a familiarity with the units of light measurement.

Candela is a unit of measurement of the intensity of a light source.

Photometry is the branch of physics dealing with the measurement of the strength of light emitted by a source or the light falling on, transmitted by, or reflected from a surface. From the early 1900s, when the science of light measurement was first seriously undertaken, candles were used as the standard sources of light. Consequently, many of the definitions and units of measurement are based on the candle. However, since 1940 the international standard unit for light sources is based on the light emitted by 1 square centimeter of a blackbody radiator heated to the temperature of solidification of platinum, providing a standard that is more exactly reproducible. This standard unit of light is called the *candela*. The difference in light emitted by this new standard and the old standard candle is less than 2%.

The Measurement of Intensity

One candela is defined as one-sixtieth the light from a 1 square centimeter blackbody heated to the freezing temperature of platinum.

Intensity (sometimes called luminous intensity) is a measure of the rate at which the source emits light in a given direction. Initially, the intensity of a source was determined by comparison to the old standard candle, with the result expressed as *candlepower*. Thus a 50-candlepower source was one that emitted light equivalent to the amount of light that would come from 50 of the standard candles. The correct unit now is the *candela*. One candela is defined as one-sixtieth the light from a 1 square centimeter blackbody heated to the freezing temperature of platinum. However, the term *candlepower* is still often used to describe intensity.

Practical sources of light such as tungsten lamps and fluorescent tubes always vary in their intensity with direction, and therefore no single measurement of intensity can completely describe such sources. Perhaps the easiest way to understand the concept of intensity is to think of a ball-shaped lawn sprinkler with many holes through which the water can flow. The intensity of such a source would be similar to the rate at which water was being emitted through one of those holes in a specific direction. Such information would be of limited value since it would not describe the variation in intensities around the ball or the total amount of water being emitted by the sprinkler.

Since the intensity of a real source changes with direction, it is desirable to learn about the distribution of intensities. Such information is usually provided by the lamp manufacturer in the form of a two-dimensional graph based on polar coordinates, an example of which is shown in Figure 1-36. In this graph, intensity is plotted against the angle on special paper, called polar-coordinate graph paper that is constructed like a protractor with the angles marked around the margins and each angle having a marked value in candelas. The zero angle is head-on to the lamp, with the intensity in this direction known as the beam intensity (candlepower). From such a graph the intensity at any desired angle can be found.

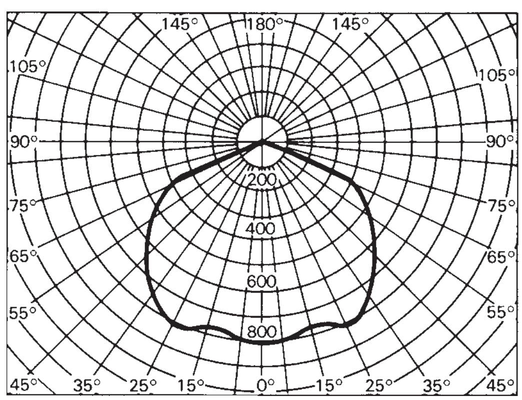

Figure 1-36 Polar-coordinate plot of intensities for a lamp-reflector combination.

For the lamp-reflector combination illustrated in Figure 1-36, the beam intensity is approximately 800 candelas. This intensity is nearly uniform, within 25° on either side of the beam position, indicating that this lamp-reflector combination provides nearly uniform illumination over a 50° angle of projection. At 65° off the beam position, the intensity drops to nearly 400 candelas. The same lamp equipped with a more narrowly curved reflector would produce a distribution of intensities much narrower than what is shown in Figure 1-36. Therefore, such polar-coordinate plots give fundamental information about the nature of the light that will be emitted.

When the intensity of a source is reported as a single value, there are three ways in which this value can be obtained, as illustrated in Figure 1-37. In the simplest case, the intensity in only one direction is measured and the value reported as a single candela value. When a number of readings are taken at uniform intervals on a horizontal plane around the source and then averaged, the result is the mean horizontal intensity (candlepower) of the light source. Instead of taking a large number of individual readings, this result is obtained in ordinary practice by rotating the source rapidly upon its vertical axis while a single reading is made. The intensity of light in all directions can be determined by measuring intensities at uniform intervals around the light source. An average of these readings would give the mean spherical intensity (candlepower) of the illuminant. It should be noted that this value is related to the total light output of the lamp. In each of these cases, the intensity is determined through comparison to a standard lamp at a variety of distances.

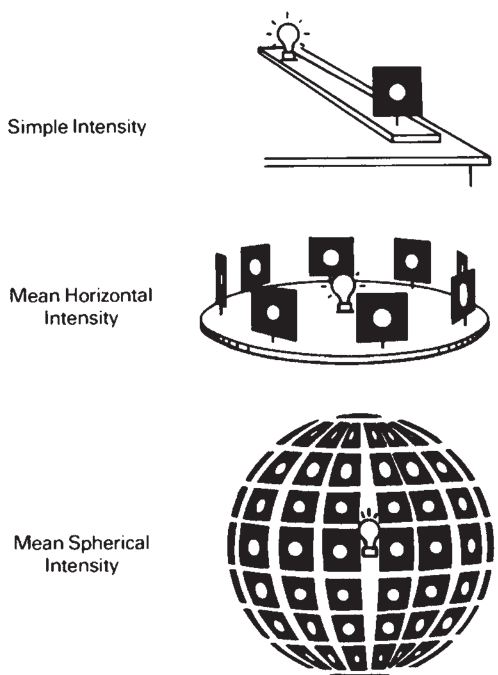

Figure 1-37 The measurement of intensity.

The Measurement of Flux

Flux (sometimes called *luminous flux*) is the rate at which a source emits light in all directions. The flux of a source is usually calculated from measurements of intensity and is closely related to the measurement of mean spherical intensity previously discussed. The unit of measurement is the *lumen*. Since flux involves the output of light in all possible directions, the lumen therefore involves a three-dimensional concept.

The *lumen* may be defined as the amount of light falling on a surface 1 square foot in area, every point of which is 1 foot from a uniform source of 1 candela (candlepower). The relationship between the candela and the lumen is illustrated in Figure 1-38. If the opening indicated by A, B, C, D is 1 square foot of the surface area of a sphere of 1-foot radius, the light escaping will be 1 lumen. If the area of this opening is doubled, the light escaping will be 2 lumens.

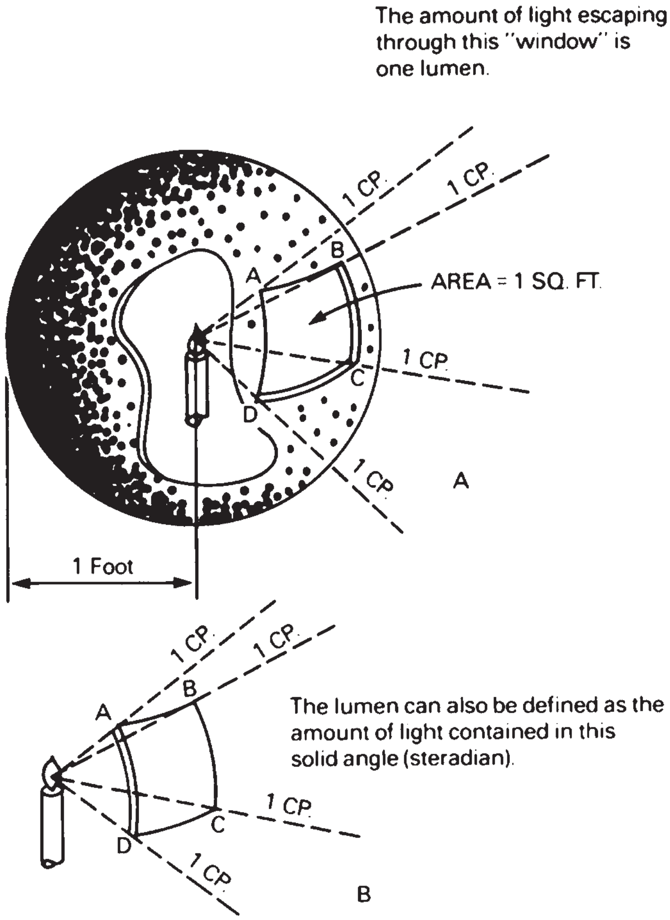

Figure 1-38 The relationship between candelas and lumens.

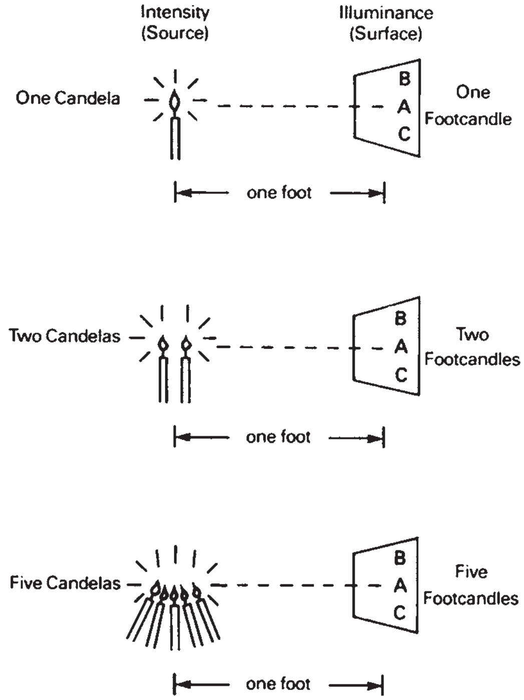

Figure 1-39 The relationship between intensity and illuminance for a constant distance of one foot.

Illuminance meters are calibrated in foot-candles and/or meter-candles (lux).

The illuminance at a distance of one meter from a one-candela source is one meter-candle. At a distance of one foot, the illuminance is one foot-candle (or 10.76 metercandles).

Since the total surface area of a sphere with a 1-foot radius is 12.57 square feet (that is, $4\pi r$), a uniform 1-candela source of light emits a total of 12.57 lumens. Thus a source of 10 mean spherical candelas emits 125.7 lumens. Since an area of 1 square foot on the surface of a sphere of 1-foot radius subtends a unit solid angle (that is, one steradian) at the center of the sphere, the lumen may also be defined as the amount of light emitted in a unit solid angle by a source having an average intensity of 1 candela throughout the solid angle. Therefore, when considering a point source that emits light equally in all directions, there will be 12.57 (4π) lumens of flux for every candela of intensity.

The Measurement of Illuminance

Let us consider a light source the cause of illumination, which is the effect or result. Since candelas and lumens are both a measure of the cause, they apply only to the light source and not the effect obtained. *Illuminance* is defined as the light incident upon a surface. For the measurement of illumination, a unit known as the *footcandle* is often used.

A footcandle represents the illumination at a point on a surface that is 1 foot distant from, and perpendicular to, the light rays from a one-candela source. For example, if the light source in Figure 1-39 has an intensity of 1 candela, the illuminance at point A, which is 1 foot distant from the source, will be equal to 1 footcandle. The illuminance at points B and C will be less because they are at greater distances than 1 foot. Therefore, an illuminance

reading applies only to the particular point where the measurement is made. By averaging the number of footcandles at a number of points, the average illumination of any surface can be obtained. This is often done when evaluating the evenness of illumination on an enlarger easel or on a copy stand.

The footcandle is the unit of measure most closely associated with the everyday use of light. To get an idea of how much light 1 footcandle is, hold a lit candle one foot from a printed page in a darkroom. The result is approximately 1 footcandle of illumination. A full moon on a clear night gives approximately 0.02 footcandle; a well-lit street gives approximately 5 footcandles; a well-lit classroom has nearly 50 footcandles of illumination; in daylight in open shade there are approximately 1,500 footcandles of illumination, and in direct sunlight approximately 12,000 footcandles. To photograph a moonlit scene at an ISO speed of 100 would require an exposure of about 10 seconds at *f*/2, plus any additional exposure required to compensate for the reciprocity effect resulting from the long exposure time.

Referring again to Figure 1-38, it is evident that the surface A, B, C, D fulfills the conditions for a surface illuminated to a level of 1 footcandle. Every point on this square foot of surface is perpendicular to the rays of a 1-candela source that is 1 foot distant. This illustrates an important relationship between lumens and footcandles. A lumen is the light flux spread over 1 square foot of area that will illuminate that area to a level of 1 footcandle. Therefore, 1 footcandle is equal to 1 lumen per square foot. This relation forms the basis of a simplified method of lighting design known as the lumen method. When the number of square

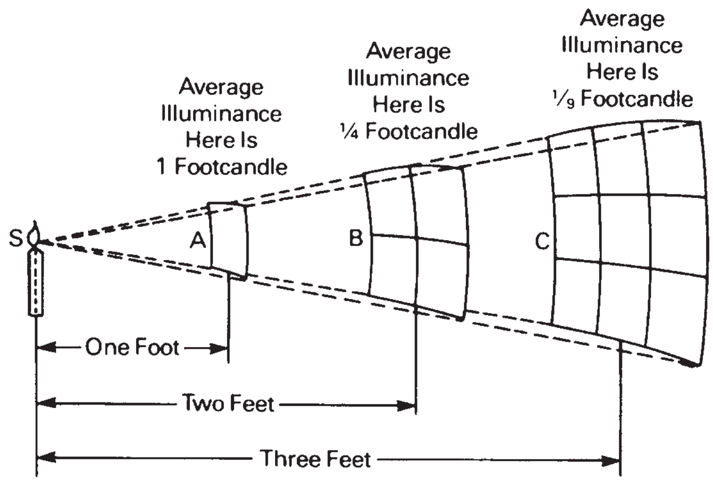

Figure 1-40 The relationship between intensity and illuminance for a constant intensity and varying source-to-surface distances (inverse square law).

feet to be lighted is known and the desired level of illumination determined, it is simple to determine the number of lumens that must be provided on the working plane.

One footcandle equals 10.76 metercandles.

With a 1-candela source, as shown in Figure 1-40, the level of illumination on point A, which is 1 foot distant, is 1 footcandle. However, if plane A is removed and the same beam of light is allowed to pass on to plane B, which is 2 feet away, this same beam of light would now cover an area four times that of plane A. The average illumination on plane B would be one-quarter as great as that on plane A, which would be equal to one-quarter of a footcandle. In the same fashion, if the beam of light is allowed to fall upon plane C, which is 3 feet away from the source, it will be spread over an area nine times as great as plane A, and so on.

One footcandle is equal to one lumen per square foot.

Thus, illumination falls off (decreases) not in proportion to the distance but in proportion to the square of the distance. This relationship is known as the *inverse-square law*. It should be emphasized that this law is based on a point source of light

Table 1-4 Standard illuminance levels for viewing reflection prints and luminance levels for viewing transparencies

ANSI PH2.30–1988	
Comparison viewing/critical appraisal	2200 ± 470 lux
Display, judging, and routine inspection	800 ± 200 lux
Transparency viewing	1400 ± 300 cd/m^2
ISO 3364:2000	
Monitor White Point D65	75–100 cd/m^2
Ambient Light	shall be less than 65 cd/m^2
	should be less than 32–65 cd/m^2

Some galleries display color prints at a low light level of only 12 footcandles (about 130 lux) to minimize fading, which protects the colors but degrades the perception of color.

The inverse-square law does not apply to luminance, which does not change with viewing or measurement distance.

The concept of luminance applies to light sources, reflecting surfaces, and transmitting surfaces.

from which the light rays diverge as shown in Figure 1-40. In practice, it applies with close approximation when the diameter of the light source is not greater than approximately one-tenth the distance to the illuminated surface. The formula for the inverse square law is as follows:

$$E = \frac{I}{d^2} \qquad \text{(Eq. 1-4)}$$

where E is the illuminance in footcandles, I is the intensity of the source in candelas, and d is the distance of the surface from the source in feet. Illuminance measurements can be used to determine the intensity (expressed as candelas) of a source by solving the above equation for I as follows:

$$I = E \times d^2 \qquad \text{(Eq. 1-5)}$$

An alternative unit to measure illuminance in photography is the metercandle. The definition of a *metercandle* is similar to that of a footcandle, except the distance from the source, *S*, to the point *A* in Figure 1-39 is 1 meter. (One metercandle is the amount of light falling on a surface at a point 1 meter from a 1-candela source.

A meter is larger than a foot, so the inverse square law governs the relationship between a metercandle and a footcandle. There are approximately 3.28 feet in 1 meter, and therefore 1 metercandle would be equal to 1 divided by 3.282, which equals 1/10.76, or 0.0929 footcandle. Therefore, 1 footcandle is equal to 10.76 metercandles. The term *metercandle* is becoming less frequently used; the preferred name is now *lux*. One lux is equal to 1 metercandle. In the photographic literature the lux (metercandle) measure of illuminance is more common than the footcandle.

When exhibiting reflection prints, the level of illumination can have a significant effect upon their appearance. Consequently, a number of standard conditions have been specified for viewing purposes and are summarized in Table 1-4. The variety of levels suggested is due in part to the differing visual tasks being performed. For example, the viewing of prints for comparison purposes requires a higher level of discrimination and, therefore, a higher illuminance level than does the viewing of a pictorial display. Further, since print judging and display involve subjective opinions, it should not be surprising that a variety of standards exist.

The Measurement of Luminance

Luminance can be defined as the rate at which the unit area of a source emits light in a specific direction. If a source is not a point source but has an appreciable size (as all real sources do), it is less useful to describe the intensity of such a source than to specify its luminance. Luminance is derived from intensity measurements, which are then related to the projected surface of the source.

Luminance is expressed in candelas per unit area (candelas per square

foot, candelas per square inch, candelas per square centimeter, depending upon the size of the surface area being considered). For example, Figure 1-41 shows a frosted tungsten lamp with an intensity of 100 candelas in the direction of point A. This lamp has a projected area in that direction of 5 square inches. The luminance in that direction would then be 100 candelas divided by 5 square inches, equal to 20 candelas per square inch.

Luminance is the *photometric* quantity that relates closely to the perceptual concept of brightness. The term brightness is used exclusively to describe the appearance of a source and, therefore, cannot be directly measured.

Generally, as the luminance of a source increases, so does the *brightness* of that source. If two 60-watt tungsten lamps are placed side by side, and one lamp is frosted while the other is clear, the clear lamp looks much brighter than the frosted lamp. If both bulbs are consuming the same amount of electrical energy and they both are using a tungsten filament, the intensities of the two lamps would be the same. However, the luminance of the clear bulb will be much greater since the projected area of the filament is much smaller than the projected area of the glass envelope on the frosted lamp. From this example it should be evident that knowledge only of the intensities of the sources would be very misleading, while knowledge of the luminance of the sources relates more directly to the perception of brightness of the sources. Consequently, luminance data for real sources are always preferred over intensity data when the visual appearance of the source is desired.

The concept of luminance applies to reflecting and transmitting surfaces as well as to light sources, since it

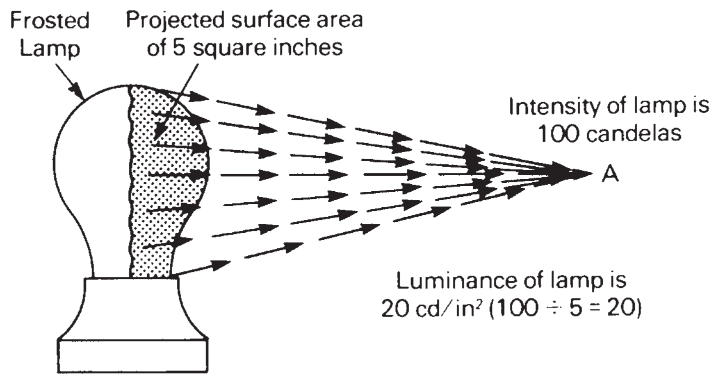

Figure 1-41 The concept of luminance.

makes no difference whether the surface being considered is originating the light or merely reflecting or transmitting the light. In this respect, if all of the light falling on a perfectly diffusing surface were reradiated by the surface, the luminance would be numerically equal to the illuminance. This does not happen, since real surfaces never reflect 100% of the light that strikes them. For this reason, it is necessary to determine the reflection factor of the surface, which is the ratio of the reflected light to the incident light. The following formula may be used:

$$\text{Reflectance factor (K)} = \frac{\text{Reflected light}}{\text{Incident light}} \quad \text{(Eq. 1-6)}$$

Appling this formula to a perfectly diffusing surface, luminance equals illuminance multiplied by the reflection factor.

The most commonly used unit of luminance when considering reflecting surfaces is candelas per square foot, and the formula is:

$$L = \frac{K \times E}{\pi} \quad \text{(Eq. 1-7)}$$

where L is the surface luminance in candelas per square foot, E is footcandles incident on the surface, and

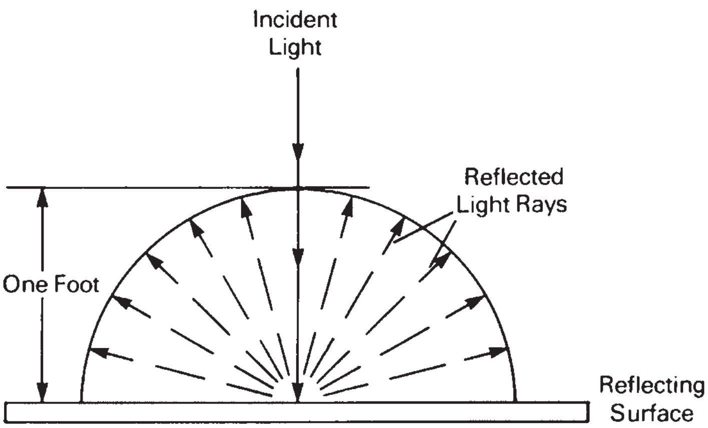

Figure 1-42 A perfectly diffusing surface; sometimes referred to as a lambertian surface.

Table 1-5 Illuminance–luminance conversions (examples based on 18 percent reflectance neutral test card)

Illuminance to Luminance
Luminance = Illuminance × reflectance
1. Footlambert = footcandle × reflectance
Luminance = 1.0 footcandle × 0.18 = 0.18 footlambert
2. Apostilb = metercandle × reflectance
Luminance = 1.0 metercandle × 0.18 = 0.18 apostilb
3. Candela per square foot = footcandle × reflectance/π
Luminance = 1.0 footcandle × 0.18 = 0.18/3.1416 = 0.057 C/ft.^{2}
4. Candela per square meter = metercandle × reflectance/π
Luminance = 1.0 metercandle × 0.18 = 0.18/3.1416 = 0.057 C/m^2
Luminance to Illuminance
Illuminance = luminance/reflectance
1. Footcandle = footlambert/reflectance
Illuminance = 1.0 footlambert/0.18 = 5.56 footcandles
2. Metercandle = apostilb/reflectance
Illuminance = 1.0 apostilb/0.18 = 5.56 metercandles
3. Footcandle = candela per square foot × π/reflectance
Illuminance = 1.0 candela/ft.^{2} × 3.1416/0.18 = 17.45 footcandles
4. Metercandle = candela per square meter × π/reflectance
Illuminance = 1.0 candela/m^2 × 3.1416/0.18 = 17.45 metercandles

Notes:

1. A perfectly diffusely reflecting surface (100 percent) illuminated by 1 footcandle (1 lumen per square foot) will reflect 1 footlambert (1 lumen per square foot or 1/π candela per square foot).
2. Metric: A perfectly diffusely reflecting surface (100 percent) illuminated by 1 metercandle (1 lumen per square meter or 1 lux) will reflect 1 apostilb (1 lumen per square meter or 1/π candela per square meter).

K is the reflection factor of the surface. As shown in Figure 1-42, the product of the reflectance and the illuminance must be divided by π (3.14), since the light is actually being emitted into a hemisphere of unit (1-foot) radius, and IT is the ratio of the radius to the surface area of the hemisphere (IT $= A/(2r)^2$). For example, if a perfectly diffusing surface with 18% reflectance is being illuminated with 100 footcandles of light, the luminance of that surface is found by multiplying 0.18 by 100 divided by 3.14, which equals 5.73 candelas per square foot.

To avoid the necessity of dividing by π all the time, the concept of a footlambert was invented. The footlambert is defined as 1 divided by π candelas per square foot. Thus the above relationship reduces to:

$$L = K \times E \qquad \text{(Eq. 1-8)}$$

where L is now expressed in footlamberts. The footlambert is actually defined as the luminance of a 100% reflecting surface illuminated by 1 footcandle of light. Therefore, the luminance of the gray card described previously would be found by multiplying 0.18 × 100 footcandles, which equals 18 footlamberts. Although the calculations are simpler for footlamberts, many modern photoelectric meters read the luminance directly in candelas per square foot, and therefore this is the more commonly used unit of measurement in photography. (These examples assume that the illuminated surfaces are perfectly diffusing or reflecting equally in all directions. This is approximately true for matte surfaces. However, shiny surfaces give highly directional reflections and do not follow these formulas.)

The concept of luminance is particularly useful in photography since it

provides a way of describing the light reflected from the surfaces of the subject being photographed. Whenever a reflected-light meter reading is made, it is a luminance measurement. Luminance measurements have the unique characteristic of being independent of the distance over which the measurement is made. For an example, if a hand-held meter with a 50° angle of view is used to measure the reflected light from a surface, the luminance obtained will be identical to that taken with a spot-meter on the same area at the camera position. The reason for this independence is that as the amount of light being measured from the original area decreases with increasing distance, the projected surface area included in the angle of view increases in direct proportion. Thus, the number of candelas per square foot will remain the same. This assumes, of course, a clear atmosphere exists between the meter and the surface area being measured, which is usually the case. The various conversions of illuminance data to luminance data are summarized in Table 1-5.

The photometric concepts discussed above are often employed to describe the properties and characteristics of all types of light sources. Table 1-6 summarizes the basic light terms and presents typical values for comparison purposes. It is obvious from this table that light sources can be described in a wide variety of ways. It is important to understand the differences in order to obtain appropriate information.

Reflected-light exposure meters measure luminance. Incident-light exposure meters measure illuminance.

Conversion tables make it easier to compare different units of measurement of light.

Table 1-6 Ten basic light terms with typical examples of each

Popular Concept	Technical Term	Symbol	Unit	Abbreviation	Measurement (Practical)
1. Strength	Luminous intensity	I	Candela	c	Compute from illuminance and distribution
2. Strength	Luminous flux	F	Lumen	lm	1 (Mfr. data) or estimate watt × luminous efficiency
3. Strength/watt	Luminous efficiency	μ	Lumens/watt	lm/W	2 (Mfr. data)
4. Total light	Luminous energy	Q	Lumen-second	lm-sec	3 (Mfr. data) or integrate area under curve
5. Color	Wavelength	λ	Nanometer	nm	Spectrometer (electronic) Spectroscope (visual) Spectrograph (photographic)
6. Color balance	Color temperature	CT	Degree Kelvin	K	4 (Mfr. data) or color-temperature meter
7. Source conversion	Mired shift		Mired	MSV	5 (Mfr. data) or compute: $\mu rd = 10^6/K_1 - 10^6/K_2$
8. Brightness	Luminance	L	Candela/sq. foot	c/ft.^{2}	Reflected-light meter
9. Illumination	Illuminance	E	Footcandle Metercandle Lux	ftc (fc) mc	Incident-light meter with flat surface
10. Exposure	Photographic exposure	H	Footcandle-second Metercandle-second	ftc-sec mc-sec	Compute H = illuminance × time:

Note: Concepts 1–8 apply to light sources. Concept 8, Luminance, also applies to reflected and transmitted light. Concepts 9–10, Illuminance and Photographic exposure, apply to light falling on a surface.

REVIEW QUESTIONS

1. Diffraction of light that passes through small opening is more easily explained with the . . .

   A. wave theory
   B. quantum theory

2. The maximum sensitivity of the human eye, with moderate to high levels of luminance, is at a wavelength of approximately . . .

   A. 500 nm
   B. 550 nm
   C. 600 nm
   D. 650 nm
   E. 700 nm

3. The seven hues that can be identified in the spectrum of white light by most people with normal color vision are . . .

   A. blue, blue-green, green, yellow-green, yellow, orange, red
   B. violet, blue, green, yellow, yellow-orange, orange, red
   C. violet, blue, blue-green, green, yellow, orange, red
   D. blue, green, red, cyan, magenta, yellow, white

4. As the temperature of a blackbody increases, the wavelength at which the peak output of radiation occurs . . .

   A. becomes smaller
   B. remains constant
   C. becomes larger

5. A color temperature rating of 3200 K for a studio lamp signifies that . . .

   A. the temperature of the tungsten filament is 3200 K
   B. the spectral energy of the light emitted matches that of a blackbody at a temperature of 3200 K
   C. the light emitted visually matches that emitted by a blackbody at a temperature of 3200 K

6. The higher the color temperature of a light source, the . . .

   A. bluer the light
   B. redder the light

7. The maximum amount of polarized light in light reflected from nonmetallic surfaces occurs at an angle to the surface of approximately . . .

   A. 25 degrees
   B. 35 degrees
   C. 45 degrees
   D. 55 degrees

8. An advantage tungsten-halogen lamps have over conventional tungsten lamps is that the tungsten-halogen lamps . . .

   A. remain more constant in light output with use
   B. operate at a lower temperature
   C. are less expensive to purchase
   D. produce light of daylight quality

9. The correlated color temperature of unfiltered electronic flash lamps is approximately . . .

   A. 3200 K
   B. 5000 K
   C. 5500 K
   D. 6000 K

10. A distinctive feature of laser light is that it . . .

    A. is plane polarized
    B. contains an equal amount of all wavelengths in the visible part of the spectrum
    C. consists of waves that are all in phase
    D. travels at twice the speed of ordinary light
    E. cannot penetrate ordinary window glass

11. The candela, as a unit of measurement, is based on the light emitted by . . .

    A. a candle
    B. a candela
    C. melted platinum
    D. a heated blackbody

12. The illuminance at a distance of 1 foot from a light source with a luminous intensity of 10 candelas is . . .

    A. 1 footcandle
    B. 10 footcandles
    C. 100 footcandles
    D. 126 footcandles
    E. 200 footcandles

13. The term *lux* is a synonym for . . .

    A. footcandle
    B. metercandle

14. The concept of luminance applies to . . .

    A. light sources only
    B. reflecting surfaces only
    C. both light sources and reflecting surfaces

15. When the luminance of a surface of uniform tone is measured with a spot exposure meter, the luminance will vary . . .

    A. directly with the meter to surface distance
    B. inversely with the meter to surface distance
    C. directly with the meter to surface distance squared
    D. inversely with the meter to surface distance squared
    E. none of the above

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chapter 2

Camera and Printing Exposure

Photograph by David Kelbe, Imaging Science Student, Rochester Institute of Technology

Camera Exposure Versus Photographic Exposure

Although the terms camera exposure and photographic exposure are related, they are not the same. The term *camera exposure* refers to the combination of shutter speed and *f*-number used to expose an image. *Photographic exposure* is defined as the quantity of light per unit area received by the film, photosensitive material, or digital sensor, and it is calculated by multiplying the illuminance (H) and the exposure time (t). The relationship is commonly expressed as $H = E \times t$.

Assuming that a camera shutter is accurate, the shutter setting is a measure of exposure time (t), but the *f*-number setting is not a measure of the illuminance. In a typical picture-making situation, the film or sensor receives many different photographic exposures in different areas. Opening the diaphragm by one stop doubles all the different illuminances that constitute the light image on the film or sensor. The *f*-number and shutter settings on a camera enable the photographer to control the photographic exposures received by the film or sensor, even though the quantitative values of those exposures are not known. The function of an exposure meter is to determine a combination of *f*-number and shutter speed settings that will produce a correctly exposed photograph, taking into account the amount of light falling

Relative aperture is the same as *f*-number, but camera exposure is not the same as photographic exposure.

F-Number = focal length/(effective aperture)

The larger the *f*-number the smaller the aperture.

on or reflected by the subject and the speed rating of the light-sensitive material being exposed.

F-Numbers

Relative aperture is another name for *f*-number. The value of the relative aperture or *f*-number depends upon two things: the *focal length* of the lens and the *effective aperture*. The effective aperture is defined as the diameter of the entering beam of light that will just fill the opening in the diaphragm of a camera lens or other optical system. The diameter of the opening in the diaphragm is known as the *aperture*. When the diaphragm is located in front of a lens, the effective aperture is the same as the aperture, as illustrated in Figure 2-1. Rarely is the diaphragm located in front of a photographic lens, which makes it necessary to take into account any change in direction of the light rays between the time they enter the lens and when they pass through the diaphragm opening. Since a lens compresses the entering beam of light into a converging cone, a diaphragm with a fixed aperture will transmit more light when it is located behind the lens than in front (see Figure 2-2).

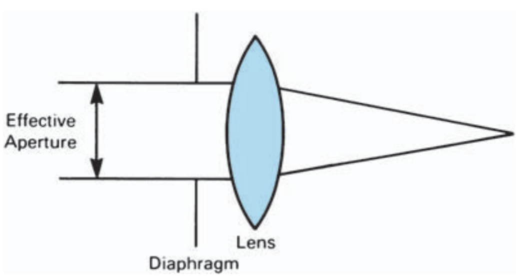

Figure 2-1 When a diaphragm is located in front of a lens, the effective aperture is the same as the aperture or diaphragm opening.

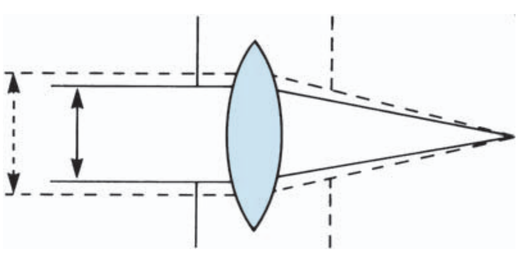

Figure 2-2 A diaphragm will transmit more light when located behind the lens than in front.

Calculating *F*-Numbers

F-numbers are calculated by dividing the lens focal length (f) by the effective aperture (D), or f-number $= f/D$. Since the effective aperture is rarely the same size as the aperture (the physical opening in the diaphragm), the diameter of the entering beam of light that just fills the diaphragm opening must be measured. One method to determine this diameter is to place a point source of light one focal length behind the lens so the diaphragm opening restricts the beam of light emerging from the front of the lens. This beam will be the same size as an entering beam that just fills the diaphragm opening (see Figure 2-3). The diameter of a beam of light can be measured with a ruler in front of the lens.

Focusing the lens on a distant object, such as the sun, and measuring

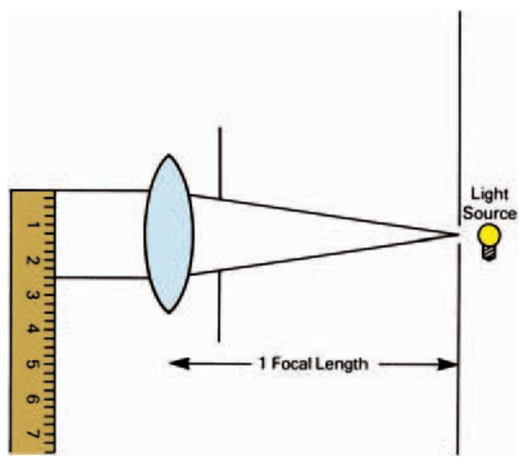

Figure 2-3 A procedure for determining the effective aperture is to place a point source of light one focal length behind the lens and measure the diameter of the beam of light that emerges from the front of the lens.

the distance from the middle of the lens to the sharp image can determine the focal length of a simple lens. (A more precise procedure is described in Chapter 4, Photographic Optics.) If the focal length of an uncalibrated lens is found to be 8 inches, and the diameter of the effective aperture at the maximum opening is 1 inch, the *f*-number is the focal length divided by the effective aperture—8/1, or *f*/8. Note that when the lens is stopped down so that the effective aperture becomes smaller, 1/2 inch, for example, the *f*-number becomes larger since 8 divided by 1/2 is *f*/16. The *f*-numbers become larger as the diaphragm is stopped down and the amount of light transmitted by the lens becomes smaller, however this relationship is not a simple inverse ratio. The reason for this is that *f*-number is based on the diameter of the entering beam of light, whereas the relative amount of light transmitted is based on the area of a cross section of the beam of light. The relationship between the area (A) and the diameter of a circle (D) is $A = \pi \times D^2/4$. Thus the amount of light transmitted by a lens varies directly with the diameter squared (D^2) and inversely with the *f*-number squared.

Whole Stops

Photographers find it useful to know the series of *f*-numbers that represent whole stops: *f*/0.7, 1.0, 1.4, 2.0, 2.8, 4, 5.6, 8, 11, 16, 22, 32, 45, 64. The *f*-number series can be extended in either direction by noting that the factor for adjacent numbers is the square root of 2, or approximately 1.4. Also note that alternate *f*-numbers vary by a factor of 2, with a small adjustment between 5.6 and 11, and between 22 and 45, to compensate for the cumulative effect of fractional units.

Each time the diaphragm is stopped down one stop (e.g., from *f*/8 to *f*/11), the amount of light transmitted is divided by two, and the exposure time required to obtain the same photographic exposure on the film is multiplied by two.

Maximum Diaphragm Openings

The *f*-number range on most camera lenses is approximately seven stops. A typical 35-mm camera lens may have, for example, a range from *f*/1.4 to *f*/16 (seven stops), and a typical view camera lens may have a range from *f*/5.6 to *f*/45 (six stops). There has been a constant demand over the years for lens designers to make faster and faster lenses. In the 1940s, *f*/2 lenses were considered fast for 35-mm cameras. Now *f*/0.7 lenses are mass-produced, a gain of three stops. The fastest one-element lens that can be made with conventional optical design is *f*/0.5. Such a lens would be half a glass sphere with the film in contact with the flat surface, as illustrated in Figure 2-4.

The need to make photographs under very low light levels, such as moonlight and even starlight for surveillance and other purposes, has led photographic engineers to explore alternatives to the difficult task of further increasing the speed of lenses

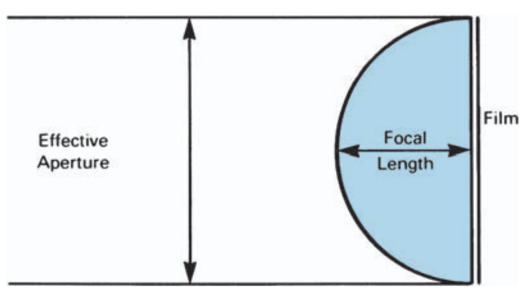

Figure 2-4 An *f*/0.5 lens, where the lens is half a sphere. The focal length is the radius of the sphere, and the effective aperture is the diameter.

***f*/2 is two stops faster than *f*/4.**

Common *f*-number series: *f*/0.7, 1.0, 1.4, 2.0, 2.8, 4, 5.6, 8, 11, 16, 22, 32, 45, 64.

The fastest single-element glass lens that can be made is *f*/0.5.

and films. The most successful are "image-intensifiers," which can electronically amplify the light image formed by the camera lens by as much as 30,000 times. To achieve the same effect by designing a lens faster than *f*/0.7 would require an *f*-number of *f*/0.004, which represents an increase in speed of approximately 15 stops. To achieve the same effect by making film faster than ISO 400/27° would require the film to have a speed of ISO 12,000,000/72°. With image intensifiers that are now available, it is necessary to trade off some resolution of fine detail for the increase in speed.

Figure 2-5 Photograph made in 1912 by Ralph Steiner, originator of the East Coast *f*/180 School, using a pinhole in combination with a camera lens (photograph by Ralph Steiner).

Minimum Diaphragm Openings

Depth of field increases as a lens is stopped down, therefore it would seem desirable to mark *f*-numbers down to very small openings on all lenses. In 1932, a group of photographers including Ansel Adams, Imogen Cunningham, and Edward Weston formed an organization called Group *f*/64, with the name implying that they favored making photographs in which everything was sharp.[1] Later, Ralph Steiner used a pinhole with his camera lenses and began his own East Coast *f*/180 School (see Figure 2-5).[2]

Although stopping down increases depth of field, it also increases the diffraction of light, which tends to reduce image sharpness overall. With a lens stopped down to *f*/64, the maximum resolving power that can be obtained—no matter how good the lens or accurate the focusing—is approximately 28 lines/mm. For an 8 × 10-inch camera this is quite good because 10 lines/mm is considered adequate in a print viewed at a distance of 10 inches. Stopping a 35-mm camera down to *f*/64 would produce the same resolving power of 28 lines/mm in the negative, but since the negative must be enlarged eight times to obtain an 8 × 10-inch print, the resolving power in the print would be only 28/8, or 3.5 lines/mm. (The calculation of diffraction-limited resolving power is discussed in the Photographic Optics chapter.) Lens manufacturers

[1] Newhall, B. *The History of Photography*. New York: Museum of Modern Art, 1984, p. 128.
[2] Steiner, R. *Ralph Steiner: A Point of View*. Middletown, CT: Wesleyan University Press, 1978, p. 9.

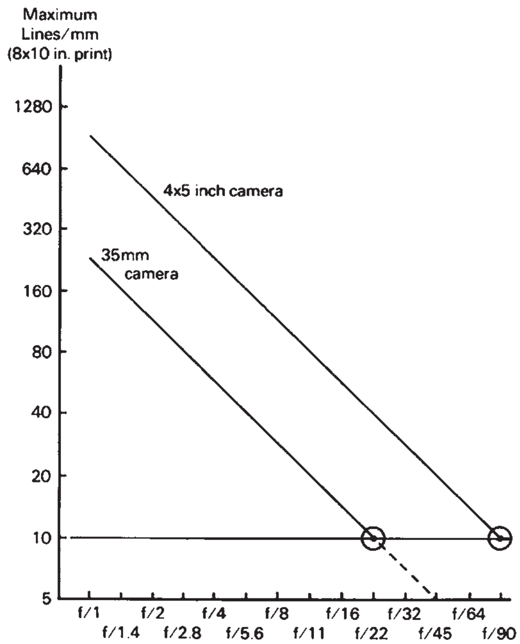

Figure 2-6 The sloping lines show that the diffraction-limited resolving power decreases as a lens is stopped down. A just-acceptable resolving power of 10 lines/mm is reached at *f*/22 with a 35-mm camera and at *f*/90 with a 4 × 5-inch camera. Resolving-power values are based on 8 × 10-inch prints, which represent a magnification of 2 for 4 × 5-inch negatives and 8 for 35-mm negatives.

normally do not calibrate lenses for 35-mm cameras for openings smaller than *f*/22 because at that opening the diffraction-limited resolving power is approximately 80 lines/mm in the negative or 10 lines/mm in an 8 × 10-inch print (see Figure 2-6).

Intermediate *F*-Numbers

There are situations in which it is necessary to know the *f*-number of divisions smaller than whole stops, such as 1/3, 1/2, or 2/3 stop larger or smaller than a given *f*-number. (Many lenses have click-stops to obtain 1/2-stop settings, and modern exposure meters can display down to 1/10-stop differences.) Intermediate values can be determined easily on instruments having interval scales, such as thermometers and balances for weighing chemicals, by measuring or estimating between markings or numbers. The *f*-number series, on the other hand, is a ratio scale in which each number is determined by multiplying or dividing the preceding number by a constant factor—the square root of 2 (approximately 1.4) for whole stops. For 1/2 stops the factor is the square root of 1.5 (1.22). For 1/3 stops the factor is the square root of 1.33 (1.15), and for 2/3 stops the factor is the square root of 1.67 (1.29). Multiplying *f*/2, for example, by these factors to determine *f*-numbers that represent stopping down by 1/3, 1/2, 2/3, and 1 stop, the *f*-numbers are *f*/2.30, f/2.45, *f*/2.58, and *f*/2.8.

Limitations of the *F*-Number System

F-numbers quite accurately indicate the change in the amount of light transmitted by the lens and therefore the change in the exposure received by the film or sensor in the camera. *F*-numbers cannot be relied upon to provide the correct exposure based on exposure meter readings of the light falling on a subject or reflected by a subject. The most obvious shortcoming of the *f*-number system is that it is based on the focal length of the lens. The only time the film or sensor is located one focal length from the lens is when the camera is focused on infinity, which only happens occasionally.

The square root of 2 is the factor needed to calculate a whole-stop change between *f*-numbers.

As a result, when the camera is focused on objects that are closer than infinity (image distance is larger than 1 focal length), it is necessary to make adjustments to the exposure. In practice, it is usually not necessary to make any adjustment until the camera is focused on a distance equal to 10 times the lens focal length or closer. At an

The *f*-numbers marked on lenses are accurate only when the camera is focused on infinity.

A 1-to-1 closeup photograph requires a four-times increase in the exposure.

object distance of 10 focal lengths, the exposure error would be 23% or about one-quarter stop if no adjustment were made. With short focal-length lenses 10 focal lengths is a small distance, only 20 inches, for example, with a normal 50-mm or 2-inch focal-length lens on a 35-mm camera. With a normal 12-inch focal length lens on an 8 × 10-inch view camera, on the other hand, 10 focal lengths amount to an object distance of 10 feet. It can be dangerous to assume that an exposure correction is necessary only when the camera is focused on a very close object.

There are various methods for making the adjustment when photographing objects that are within the 10-focal-length range. One method is to calculate the *effective f-number*, and then determine the exposure time for that number rather than for the *f*-number marked on the lens. The effective *f*-number is found by multiplying the marked *f*-number by the ratio of the image distance to the focal length, or

$$\text{Effective } f\text{-number} = f\text{-number} \times \frac{\text{Image Distance}}{\text{Focal Length}} \qquad \text{(Eq. 2-1)}$$

With lenses of normal design, the image distance is approximately the distance from the center of the lens to the film or sensor plane. (The procedure for determining the image distance with telephoto and other special lenses is covered in Chapter 4.) For example, if the image distance is 16 inches (406 mm) for a close-up photograph with a 4 × 5-inch view camera equipped with an 8-inch (203 mm) focal-length lens, the effective *f*-number when the lens is set at $f/11$ is $f/11 \times 16/8 = f/22$. When an exposure meter reading is made, the exposure time for $f/22$ would be used even though the lens is set at $f/11$. There is a two-stop difference between $f/22$ and $f/11$; the exposure meter will indicate four times the uncorrected exposure time at $f/11$ (see Figure 2-7).

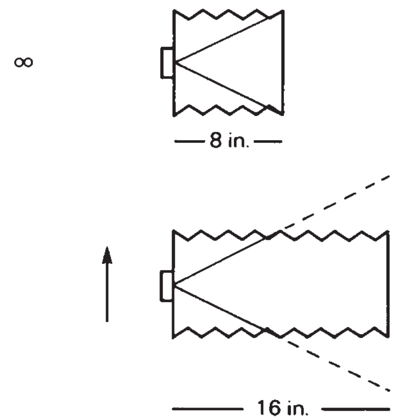

Figure 2-7 *F*-numbers are based on an image distance of one focal length (above). Doubling the image distance to photograph a close-up object produces an effective *f*-number that is double the marked *f*-number; that is, a lens set at *f*/8 acts as though it is set at *f*/16.

An alternative method for determining the exposure correction is to divide the image distance by the focal length and square the result. In the previous example, the exposure factor equals $(16/8)^2$ or 4. The correction can be applied either by using the indicated exposure time and opening the diaphragm two stops from $f/11$ to $f/5.6$, or by multiplying the exposure time indicated for $f/11$ by 4.

Lens Transmittance

A second shortcoming of *f*-numbers is they do not account for differences between lenses with respect to the amount of light lost because of absorption and reflection by the lens elements. No lens can transmit 100% of the light that strikes it. The introduction of anti-reflection coating for

lenses has reduced variability between lenses caused by this factor, but in situations where accurate exposures are essential, an adjustment is appropriate. This is a major concern in television and cinematography where exposure latitudes are small. This problem can be greater for lenses with many elements, for example, an early zoom lens for 35-mm cameras was approximately three-quarters of a stop slower than indicated by the *f*-number because of the large number of elements, even though they were coated.

The *T-number* system of calibrating lenses based on the lens transmittance was devised as an alternative to the *f*-number. Two lenses may have the same *f*-number, indicating they are the same speed, but different *T*-numbers. This could be caused by differences in the number of lens elements and construction of the lens or to differences in lens coatings. Two lenses set at the same *T*-number will always produce the same image brightness under identical lighting conditions. As a simple example, if a lens marked *f*/2 in the *f*-number system transmits only one-half the light that falls on the lens, it would be recalibrated as *T*/2.8. See Eq. 2-2 for an example. When an exposure meter reading is made, the exposure time is then selected for *f*/2.8 rather than for *f*/2, and the longer exposure time would exactly compensate for the loss of light caused by absorption and reflection. *T*-number is defined as the *f*-number of an ideal lens of 100% transmittance that would produce the same image illuminance on axis as the lens under test at the given aperture.

$$T\text{-number} = \frac{f\text{-number}}{\sqrt{T}} = \frac{2}{\sqrt{0.5}} = 2.8 \qquad \text{(Eq. 2-2)}$$

Exposure Time

Photographers can vary either of two factors to alter the exposure received by the film or other light-sensitive material, namely illuminance (*f*-number) or time (shutter speed). In many picture-making situations, the photographer has a choice of any of a number of combinations of *f*-numbers and shutter speeds, all of which will produce the same level of photographic exposure but with different depth-of-field and action-stopping characteristics.

Rule of thumb: The slowest safe shutter speed for handheld 35-mm cameras is 1/the focal length of the lens in millimeters—1/50th of a second for a 50-mm focal-length lens.

Photographers cannot always select a shutter speed based only on the exposure time that will produce the correct exposure. When photographing a rapidly moving object it may be necessary to use a very short exposure time to prevent unwanted blurring of the image, and occasionally a photographer will select a slow shutter speed to obtain a blurred image (see Figure 2-8).

Handholding cameras at slower shutter speeds often will produce an unsharp image, especially with long focal-length lenses. The rule of thumb is that it is unsafe to handhold a 35-mm camera with an exposure time longer than the reciprocal of the focal length of the lens in millimeters—for example, 1/50 second with a 50-mm lens and 1/500 second with a 500-mm lens. Many modern cameras now offer an image stabilization or anti-shake feature that helps to reduce image blur caused by camera motion. This may allow for the mentioned rule of thumb to be stretched another two stops in shutter speed, but it is still not a replacement for a tripod.

Lens Shutters

Most shutters fall into one of two categories: *leaf or between-the-lens* (or *front*) shutters and *focal-plane* (or *back*)

A

B

Figure 2-8 Image A was exposed at *f*/4.5 for 1/250 of a second to stop the action of the water. Image B was exposed at *f*/29 for two seconds to allow the motion of the water to blur. (Photographs by Professor Glenn C. Miller, Imaging and Photographic Technology, Rochester Institute of Technology.)

shutters. The ideal position for a lens shutter is between the elements close to the optical center, which is also the ideal position for the diaphragm. These shutters are commonly referred to as *between-the-lens* shutters.

Effective Exposure Time

If a perfect shutter could be constructed, the blades would uncover the entire lens, or the entire diaphragm

opening, simultaneously. A high-speed motion picture of the operation of a lens shutter shows the blades uncovering the center of the lens first and then gradually uncovering more and more of the lens. At the higher shutter speeds, the shutter blades no sooner uncover the outer edges of the lens than they again cover them at the beginning of the closing operation. The result is that the center of the lens is uncovered for a longer time than the edges, and the total amount of light that is supposed to be transmitted by a lens is actually transmitted only during the time that the diaphragm opening is completely uncovered by the shutter blades (see Figure 2-9). If a light meter is used to measure the change in the amount of light transmitted by a lens during the operation of the shutter, we would find that the reading would increase during the opening stage, remain constant while the shutter blades remained fully open, and decrease during the closing stage. Figure 2-10 shows the change of illuminance with time in the form of a graph.

The effective exposure time of a between-the-lens shutter increases as the diaphragm is stopped down.

If lens manufacturers calibrated shutters from the time they start to open until they are completely closed again, the loss of light during the opening and closing parts of the cycle would lead to underexposure—in other words, the effective exposure time is shorter than the total exposure time. To avoid this underexposure problem, shutters are calibrated from the half-open position to the half-closed position with the diaphragm wide open, as illustrated in

With focal plane shutters, stopping down has little effect on effective exposure time.

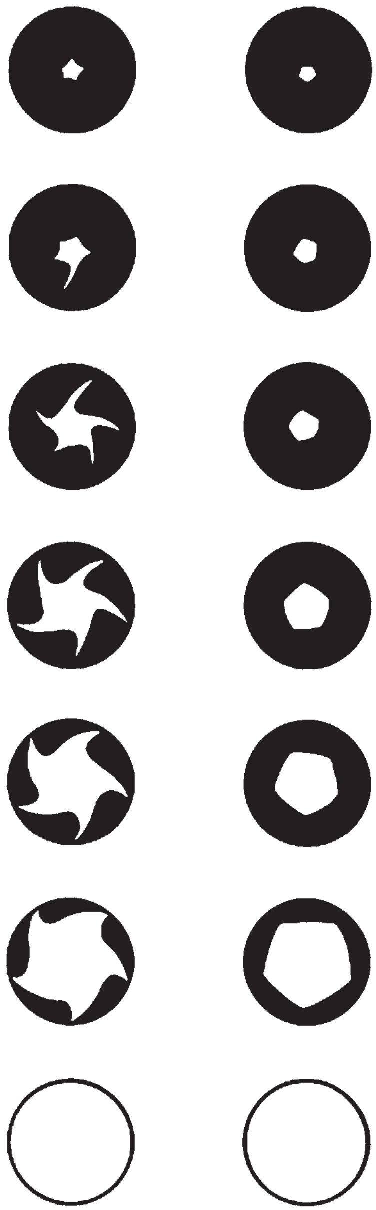

Figure 2-9 On the right are the diaphragm openings for the whole stops on a typical lens. On the left are the positions of the shutter blades at which the diaphragm openings are *just* completely uncovered. Since the smaller openings are uncovered sooner and stay uncovered longer, the effective exposure time is longer than with a larger opening and the same shutter setting.

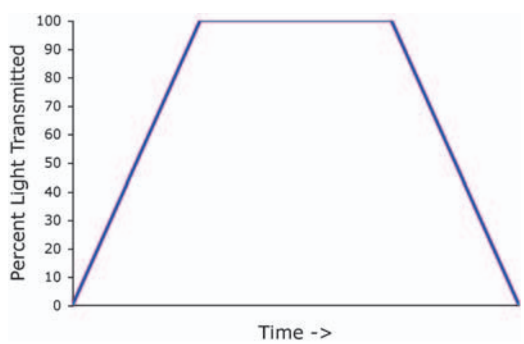

Figure 2-10 The amount of light transmitted by a lens increases as the shutter blades open, remains constant as long as the diaphragm opening is completely uncovered, and decreases as the shutter blades close.

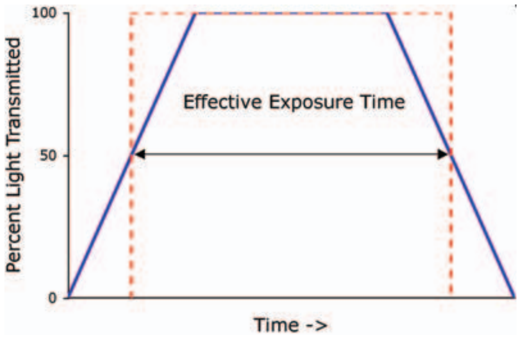

Figure 2-11 Shutters are calibrated from the half-open position to the half-closed position. The total exposure time is longer than the effective exposure time to compensate for the loss of light during the opening and closing stages of the cycle.

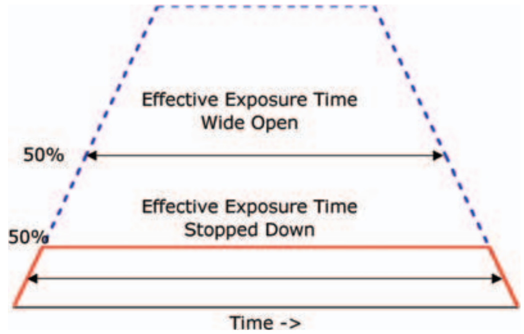

Figure 2-12 When a lens is stopped down, the smaller opening is uncovered sooner and remains uncovered longer, increasing the effective exposure time from half-open to half-closed.

A distorted image may result when photographing rapidly moving objects with a focal-plane shutter camera.

Figure 2-11. The loss of light during the opening and closing operations is compensated for by the fact that the total exposure time is longer than the time marked on the shutter.

Unfortunately, when the diaphragm is stopped down, the smaller opening is uncovered sooner and remains completely uncovered longer. As a result, the half-open to half-closed time (which is the effective exposure time) increases as the diaphragm is stopped down, even though the shutter blades are opening and closing exactly the same as when the diaphragm was wide open (see Figure 2-12).

Shutters that are calibrated with the diaphragm wide open, as is the practice, tend to overexpose images at small diaphragm openings because of the increase in the effective exposure time. The error is small at slow shutter speeds but approaches double the indicated exposure, or the equivalent of a one-stop error, at combinations of high shutter speeds and small diaphragm openings. Compensation for this error should be made by stopping down farther than an exposure meter reading indicates for the selected shutter speed, or by selecting the *f*-number specified for the *effective* exposure time rather than the marked time. Table 2-1 indicates the correction needed for different combinations of shutter speeds and diaphragm openings.

Focal-Plane Shutters

The basic design of the focal-plane shutter is a slit in opaque material placed close to the film or sensor that moves across the film from edge to edge. Exposure could be altered with early focal-plane shutters by selecting one of several slit widths in the shutter curtain and selecting one of a number of spring tensions that controlled the speed of the slit's movement. Rewinding the curtain before inserting the dark slide in the film holder resulted in fogged film. Modern focal-plane shutters have an adjustable opening between two curtains (or blades) with a self-capping feature to eliminate the slit when the curtain is rewound (see Figure 2-13).

There are several advantages of a focal-plane shutter. The first is that the shutter can be built into the camera and used with interchangeable lenses rather than placing a shutter in each lens, which reduces lens cost. A second advantage is that stopping a lens down has little effect on the effective exposure time with focal-plane shutters

Table 2-1 The correction needed for different combinations of shutter speeds and diaphragm openings

	Stopped Down							
Maximum Aperture[1]	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
f/1.4	f/2	f/2.8	f/4	f/5.6	f/8	f/11	f/16	f/22
f/2	f/2.8	f/4	f/5.6	f/8	f/11	f/16	f/22	f/32
f/2.8	f/4	f/5.6	f/8	f/11	f/16	f/22	f/32	f/45
f/4	f/5.6	f/8	f/11	f/16	f/22	f/32	f/45	f/64
f/5.6	f/8	f/11	f/16	f/22	f/32	f/45	f/64	f/90
f/8	f/11	f/16	f/22	f/32	f/45	f/64	f/90	f/128
Exposure Time[2]								
1/60	0	0	0	0	0	0 –	0 –	0 – ¼
1/125	0 – ¼	¼	¼	¼	¼	¼	¼	¼
1/250	¼	¼	½	½	½	½	½	½
1/500	½	¾	1	1	1	1	1	1

[1]Chart for determining the number of stops between a given *f*-number and the *f*-number at the maximum diaphragm opening.

[2]Additional stopping down required to compensate for changes in shutter efficiency with between the lens shutters. The reduction in exposure (in stops) required to compensate for the increase in the effective exposure time with various combinations of *f*-numbers and exposure times

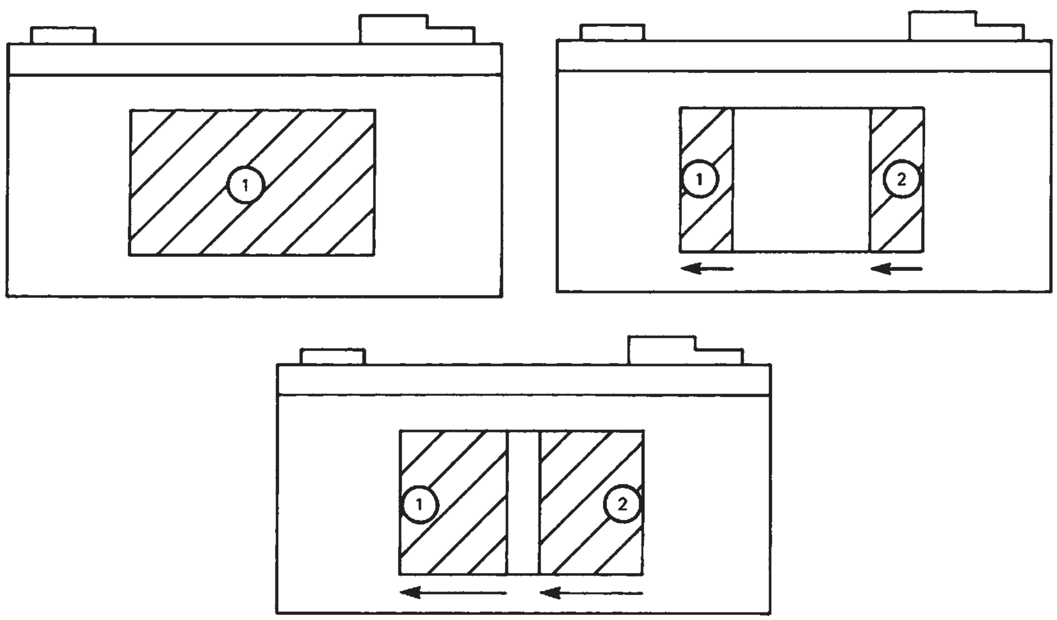

Figure 2-13 At slower shutter speeds, curtain 1, which protects the film from light before the shutter is tripped, completely uncovers the film before curtain 2 begins to cover it again. At higher shutter speeds, curtain 2 begins to cover the film before it is completely uncovered. The space between the two curtains decreases as the shutter speed increases.

so that exposure compensation is not necessary.

Disadvantages of focal-plane shutters are: changes in speed of the slit across the film or sensor result in uneven exposure (see Figure 2-14), images of rapidly moving objects are distorted in shape, and it is more difficult to synchronize flash and electronic flash at higher shutter speeds (see Figure 2-15).

Figure 2-14 Cold weather caused this focal-plane shutter to malfunction, producing variations of exposure from side to side. (Photograph by Nanette L. Salvaggio.)

Figure 2-15 Electronic-flash illumination used with a focal-plane-shutter at shutter speeds of 1/60, 1/125, and 1/250 second (top to bottom). At the higher speeds the second curtain begins to cover the film before the first curtain has completely uncovered it. The highest shutter speeds that can be used with electronic flash have increased dramatically with newer single-lens-reflex cameras and flash units.

Figure 2-15 (Continued)

Electronic Shutters

For a typical mechanical between-the-lens shutter, the power to open and close the shutter is provided by a spring that is placed under tension, and the timing is controlled by a watch-type gear train. Early focal-plane shutters on sheet-film cameras provided the photographer with two controls over the exposure time: variable tension on the spring that controlled the movement rate of the focal-plane curtain, and a choice of various slit widths in the curtain.

Electronic shutters can be divided into two categories—those using electronics to control the timing with a spring-activated shutter (more properly called electromechanical shutters) and those using electronics for both the timing and the power to activate the shutter. Electronically controlled focal-plane shutters and between-the-lens shutters (on the mass-produced Polaroid Auto-100 camera) were introduced in 1963.

The timing of electronic shutters is typically controlled by a capacitor charged by a current from a battery, which can be altered with a variable resistor, causing the shutter to close when the capacitor is filled. By adding a camera exposure meter to the circuit, the exposure time is controlled

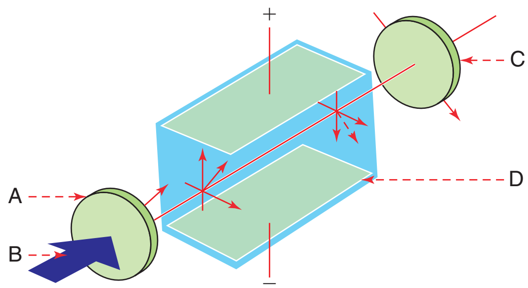

Figure 2-16 Electro-optical shutter (Kerr cell). (A) first polarizer; (B) light beam from subject; (C) second polarizer; (D) electrodes in the liquid cell. The liquid becomes birefringent on application of a high-voltage pulse to the electrodes.

automatically by the amount of light received by the meter photocell. One-way electricity is used to open and close a shutter with solenoids, where a magnetic field produced by current flowing through a coil moves a plunger and the shutter. The liquid Kerr cell, used for scientific photography, is an electronic shutter that is capable of providing exposure times as short as one-billionth of a second (see Figure 2-16).

Shutter Testing

The previous discussion concerning effective exposure times with between-the-lens shutters is based on a shutter that is accurately calibrated (at the maximum diaphragm opening) and in perfect working condition. Some shutter

It is possible for a shutter to be accurate at one speed setting, to overexpose at another setting, and to underexpose at a third setting.

Advanced design flash units that fire a burst of stroboscopic flashes can be used with some focal-plane cameras at their top speeds, such as 1/8,000 second.

The Kerr cell was invented by Rev. John Kerr in 1875.

Between-the-lens shutters are calibrated by the manufacturer at the maximum diaphragm opening.

If unsure of the correct exposure, bracket the assumed correct exposure.

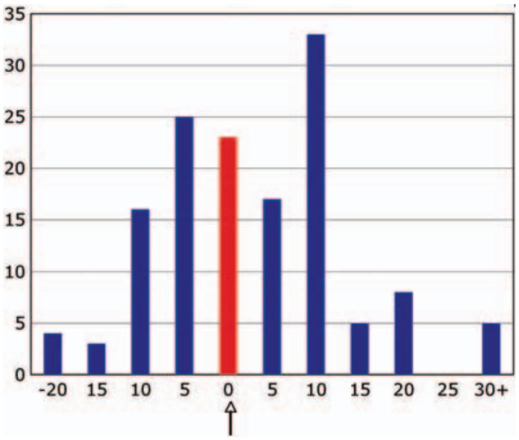

Figure 2-17 The shutters on 140 35-mm cameras were tested at a setting of 1/125 second. The range of variability is from 20% underexposure to 30% overexposure. The conversion data in Table 2-2 indicate that −20% and +30% are both equivalent to a 1/3-stop change in exposure, producing a range of 2/3 stop.

manufacturers have not guaranteed their shutters to be any more accurate than ±40% of the marked speed. In past years, it was possible to test 100 shutters selected at random representing various brands and periods of use without finding more than one or two that were accurate within ±5% at every setting. Shutters with electronic timing control tend to be more accurate than mechanical shutters, where the timing depends upon gear trains, springs and cams, but the accuracy of any shutter should not be taken for granted. Shutter variability for 140 35-mm single-lens reflex cameras is illustrated by the frequency histogram in Figure 2-17.

The most satisfactory method of testing a shutter for a film camera is with an electronic shutter tester that displays the shutter's opening and closing as a line on an oscilloscope where deviations from 100% accuracy can be determined from a calibrated grid, or where the effective exposure time is presented as a digital readout (see Figure 2-18).

Table 2-2 Conversion of percentage over- and underexposure to stops. This conversion table (see Figure 2-17) indicates that −20% and +30% are both equivalent to a 1/3-stop change in exposure

Over	Ratio Actual/Marked	Log Ratio	Stops (Log/0.3)
0%	1.0	0.00	0.00
10%	1.1	0.04	0.13
20%	1.2	0.08	0.27
30%	1.3	0.11	0.34 (1/3)
40%	1.4	0.15	0.50 (1/2)
50%	1.5	0.17	0.58
60%	1.6	0.20	0.67 (2/3)
70%	1.7	0.23	0.77
80%	1.8	0.25	0.85
90%	1.9	0.28	0.93
100%	2.0	0.30	1.00 (1)
300%	4.0	0.60	2.00 (2)
700%	8.0	0.90	3.00 (3)
Under			
0%	1.0	−0.00	0.00
10%	0.9	−0.046	0.15
20%	0.8	−0.097	0.32 (1/3)
30%	0.7	−0.155	0.52 (1/2)
40%	0.6	−0.222	0.74 (2/3)
50%	0.5	−0.301	1.00 (1)
60%	0.4	−0.398	1.33
70%	0.3	−0.523	1.74
80%	0.2	−0.699	2.33
90%	0.1	−1.000	3.33
100%	0.0	–	–

Figure 2-18 An electronic shutter tester that displays the shutter's operation as a trace on an oscilloscope.

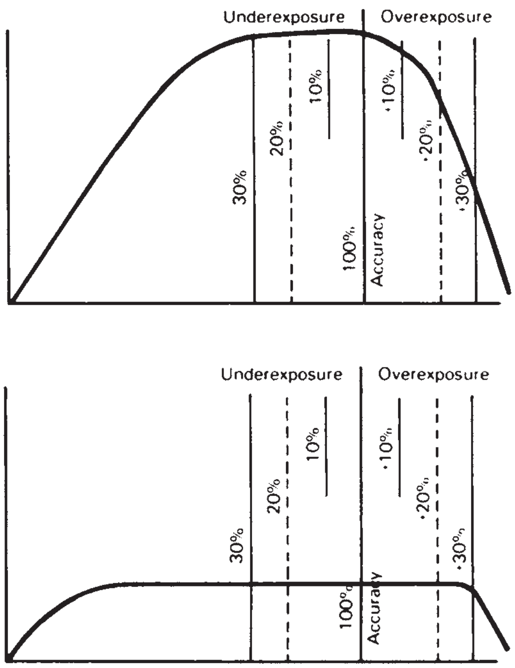

Figure 2-19 The two shutter-tester traces reveal the change in the effective speed of a between-the-lens shutter at a shutter setting of 1/250 second with the diaphragm at the maximum aperture of *f*/4 (top) and stopped down to *f*/11.

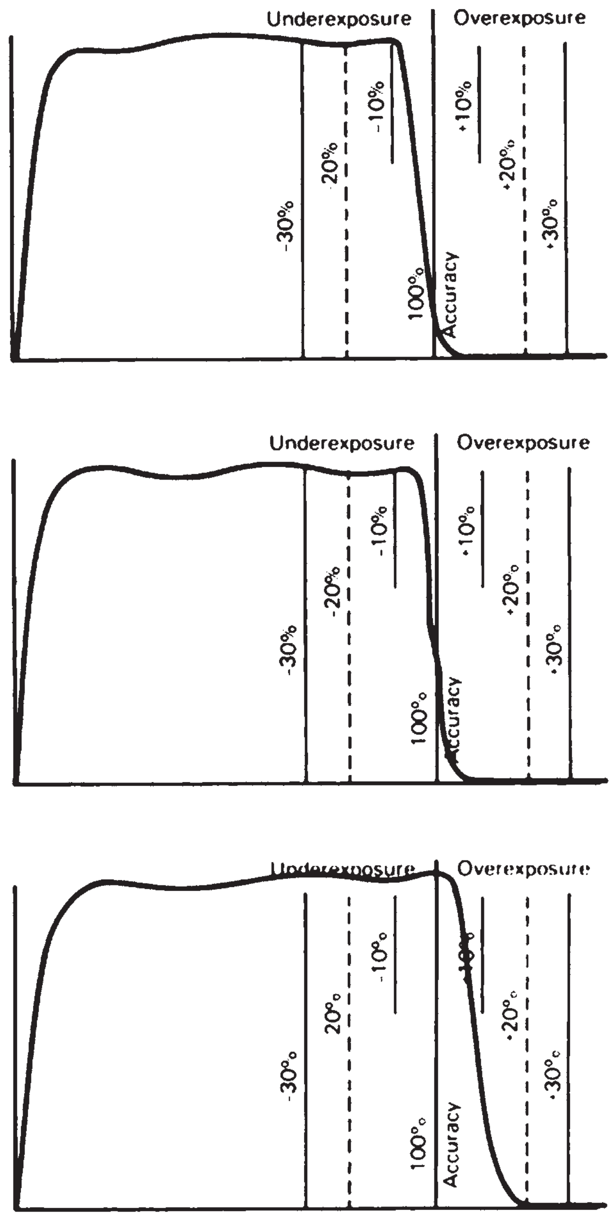

Figure 2-20 The three traces reveal the change in the effective speed of a focal-plane shutter at (from top) the right edge, center, and left edge of the film aperture. The shutter was set at 1/60 second, and the shutter traveled from right to left.

Such instruments are capable of being very accurate because they can be calibrated with the 60-cycle alternating current with which they are normally used. Such testers can also be used to determine the change in the effective exposure time of between-the-lens shutters as the diaphragm is stopped down, and to check the consistency of focal-plane shutters across the film (see Figures 2-19 and 2-20). Shutter-speed settings that are found to be inaccurate can still be used by recording the test results and then using the appropriate *f*-number for the actual shutter speed rather than for the marked speed.

In the absence of a shutter tester, a practical test can be conducted by exposing film in the camera at each setting provided certain precautions are taken. It is best to use reversal color film since it has a small exposure latitude that permits small changes in exposure to be detected. A subject having a normal range of tones should be used with front illumination. The exposure meter used should be tested against a standard light source or against a number of other meters or one meter of known accuracy, and care must be taken to make an accurate meter reading. With between-the-lens shutters the diaphragm must be

wide open, but different shutter speeds can be tested by using neutral-density filters, adding 0.3 in density each time the exposure time is doubled. With focal-plane shutters it is safe to stop down the diaphragm one stop for each change of shutter speed. Finally, it is important to be sure the film is processed normally, and the transparencies should be viewed under standardized viewing conditions.

Camera Exposure Latitude

It is safer to overexpose than to underexpose—with negative-type films.

Reversal films have much less exposure latitude than negative films.

If we assume that for every photograph made there is a combination of *f*-number and shutter speed that will produce the optimum level of exposure, photographers should know what will happen to the image quality if the level of exposure is either increased or decreased. It is unrealistic to believe that all the factors, such as film speed or sensor ISO rating, exposure meter, shutter, and *f*-number that determine the "correct" exposure are calibrated to be 100% accurate and that no human error is involved in the process. For the purpose of this discussion, however, we will make the assumption that there are no such inaccuracies. The range over which the exposure can be increased and decreased from the "correct" exposure and still produce acceptable results is known as the *exposure latitude*.

As exposure is decreased from the optimum level, which is called *underexposure*, the darker areas or shadows of the scene will first lose contrast and then detail. If we continue to reduce the exposure, the detail will be lost in progressively lighter areas of the scene, and eventually there will be no image, even in the lightest areas or highlights of the scene (see Figure 2-21).

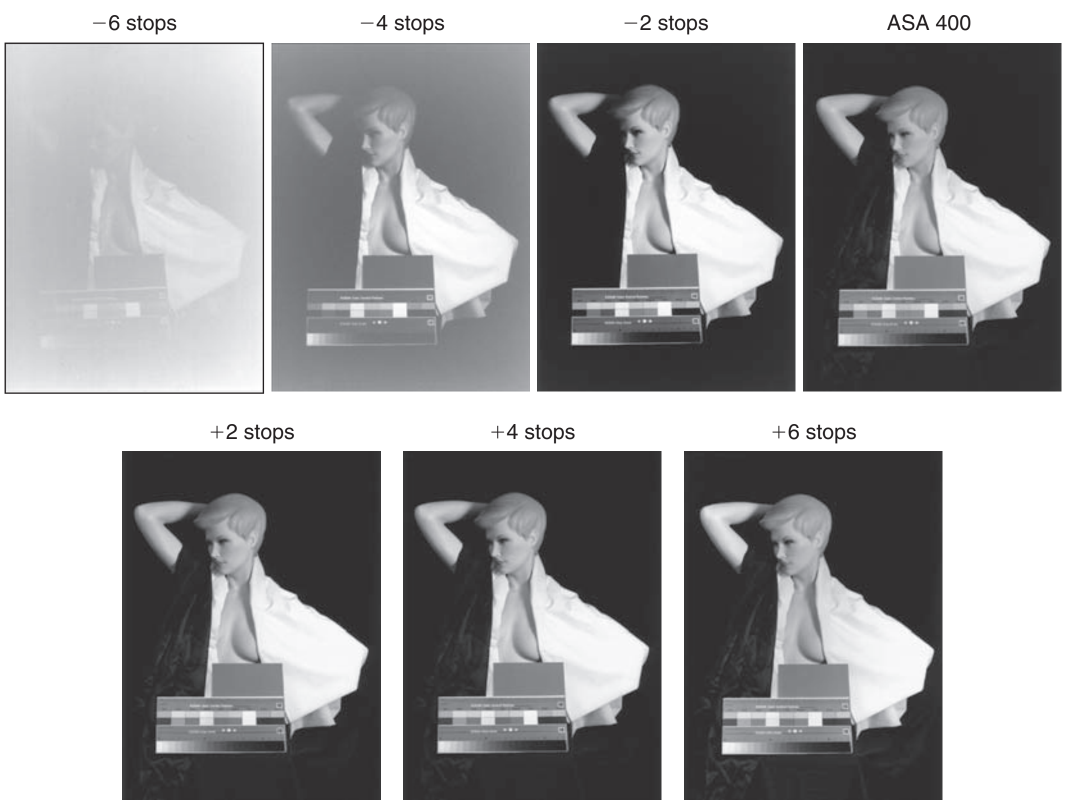

Figure 2-21 These images illustrate the influence of under- and overexposure on image quality. All prints were made of negatives from the same role of film, highlight densities were kept consistent through print exposure, and an effort was made to keep shadow densities consistent by modifying print contrast. Prints from the overexposed negatives show no negative effect on image quality. Prints from the underexposed negatives show a significant loss of image quality.

If we now take the process in the opposite direction and overexpose the images, the first noticeable change is commonly an increase in shadow contrast (and therefore an increase in overall contrast). Overexposure will also produce a decrease in image definition or, more specifically, an increase in graininess, a decrease in sharpness, and a decrease in detail. These changes may be apparent only with small-format images magnified considerably in printing. As the exposure continues to be increased, the image contrast will decrease, first in the highlight areas and then toward progressively darker areas of the scene. Seldom is all detail lost with overexposure of negative-type films, although extreme overexposure can result in a partial or complete reversal of tones known as *solarization*.

When dealing with black-and-white negative films, overall changes in contrast caused by underexposure or overexposure can be compensated for at the printing stage, but local loss of contrast and detail are not correctable. The effects of underexposure (loss of shadow contrast and detail) occur more quickly and are more severe than the effect of overexposure (modest change in contrast and decrease of definition), leading to the long-standing belief that "It is safer to overexpose than to underexpose" (see Figure 2-22). Stated in terms of exposure latitude, there is more exposure latitude on the overexposure side than on the underexposure side. These statements apply to conventional black-and-white and color negative films.

With reversal-type films the exposure latitude is small in both directions, especially when the slide, transparency, or motion-picture film exposed in the camera is the final image to be viewed—often juxtaposed spatially or temporally with other images, making relatively small density differences apparent. Changes of ±1/2 stop in exposure are commonly considered to be the maximum tolerable,

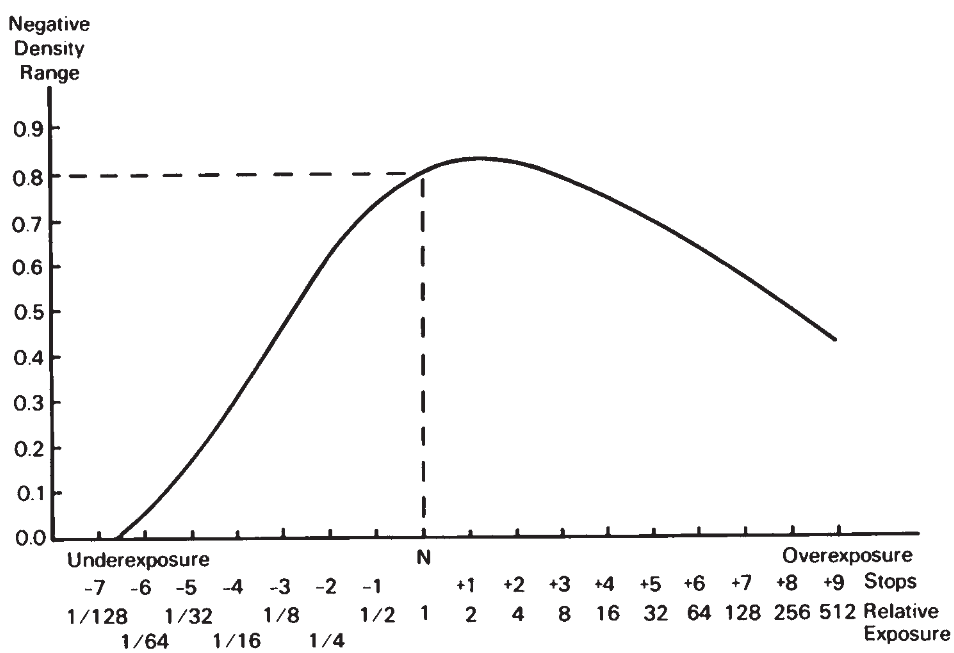

Figure 2-22 The effects of underexposure and overexposure on negative contrast are shown in this curve. Contrast decreases rapidly with underexposure. Overexposure first produces an increase in contrast before it declines at a more gradual rate.

with the possible exception of images that are viewed in isolation (as in an otherwise darkened room), viewed in comparison to other images equally underexposed or overexposed, or are to be reproduced photographically or photomechanically. Compensation in reproducing slides and transparencies is generally more successful when they are slightly dark (underexposed) than when they are too light, but this depends to some extent on the relative importance of highlight and shadow detail in each photograph. Because reversal color films have so little exposure latitude, they are especially useful for testing exposure systems.

Exposure latitude with digital sensors is more difficult to pin down. In general, digital cameras are thought to have a slightly less exposure latitude than print film does, but there are some advantages that you gain in the digital realm. Most digital cameras allow you to view the image histogram. This provides instant feedback about the exposure, thus allowing the photographer to correct any errors instantly. Bracketing the exposure is also a very viable option here. Large memory cards for cameras do not limit the user to the same number of images that can be taken as a roll of film can. Poor exposures can simply be erased. Additionally the ability to save an image in RAW format allows the photographer to "pull" information out of blocked-up shadows in software later, an option that is not possible with film. However, there is less overexposure latitude in digital cameras. Digital sensors tend to have a sharp cut-off in sensitivity at the high end of the response. Figure 2-23 provides a comparison of the exposure latitude for film and digital cameras.

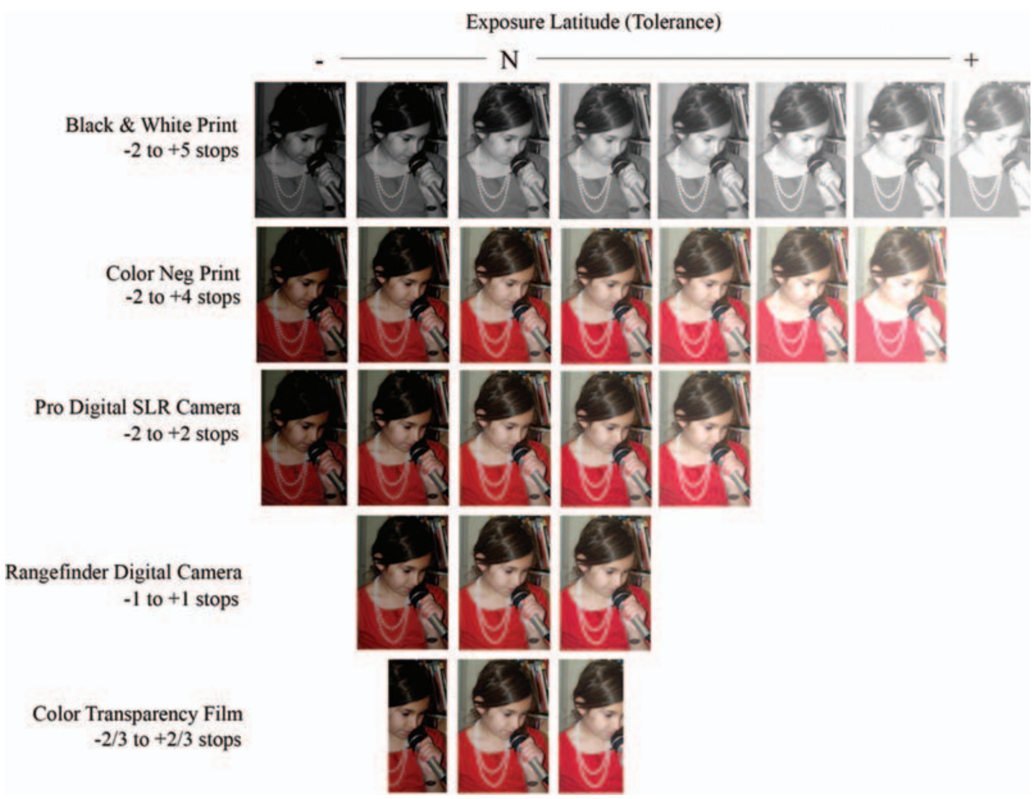

Figure 2-23 Exposure latitude for film and digital. Negative films have the greatest latitude, being greater for overexposure than for underexposure.

Alternatives to Exposure Meters

Many photographers, both professional and amateur, consider exposure meters to be as indispensable to photography as cameras, but there are other methods for determining the correct camera-exposure settings. Even trial-and-error can be used appropriately if lighting conditions are remaining constant and will be encountered again.

One of the most constant of lighting conditions is direct sunlight between the mid-morning to mid-afternoon hours. A widely used rule in this situation is the correct exposure is obtained by using a shutter speed equal to the reciprocal of the ISO speed of the film at a relative aperture of *f*/16. For example, with of ISO 125/22° a camera exposure of 1/125 second at *f*/16 would most likely produce good results. Data sheets provided for film include exposure information for other outdoor lighting conditions including hazy sun, light overcast, and heavy overcast. Exposure tables also have been used successfully for tungsten lamps, flashlamps, and electronic flash units where the lamp output and lamp-to-subject distance are constant or are measurable.

One of the most ambitious projects to provide exposure information for a variety of natural lighting conditions is the American National Standard Photographic Exposure Guide, ANSI PH2.7-1986. The exposure data for daylight are based on the latitude, time of day, sky conditions, subject classification, and direction of the lighting. Also included are data for aerial photography, underwater photography, photography by moonlight, and photographs of sunsets, rainbows, lightning, lunar and solar eclipses, and the aurora borealis. Certain artificial lighting conditions are also covered, including fireworks and television screens.

Exposure Meters

In the past, many different types of light-measuring devices or exposure meters have been used, but nearly all contemporary exposure meters are photoelectric.

Rule of thumb for exposing film outdoors in sunlight: Shutter speed at *f*/16 = 1/film speed.

Ideally, the spectral sensitivity of exposure-meter cells would closely resemble the spectral sensitivity of typical panchromatic films or modern digital sensors, but unfortunately none of them does. The curves in Figure 2-24 show the spectral sensitivity of selenium, cadmium sulfide, silicon, and silicon-blue cells. Variations of spectral sensitivity will be found among cells of the same type because of manufacturing controls, including the use of filters over the cells; and minor variations are even found among meters of the same brand and model because of the variability inherent in all manufacturing processes.

Taking exposure meter readings through filters can lead to exposure errors caused by differences in the spectral sensitivity of the meter and the film.

Blue filters, as used in silicon-blue meters, can compensate for the cells' inherently low blue sensitivity.

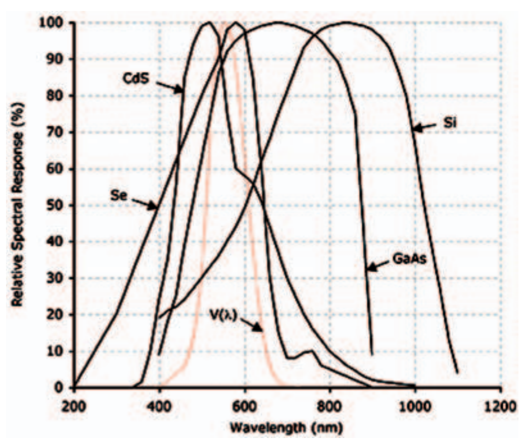

Figure 2-24 Relative spectral response functions for some common detector materials: selenium, cadmium sulfide, silicon, and gallium arsenide phosphide.

However, full correction is not an attractive option, since the filter simply absorbs the colors of light to which the cells are more sensitive, thereby reducing overall sensitivity. Silicon cells, which were introduced in the 1970s, share the high sensitivity of cadmium sulfide cells without the disadvantage of memory. Meter manufacturers are continuing to develop new types of photoelectric cells, such as silicon photodiode and gallium arsenide phosphide photodiode, in an effort to achieve further improvements in performance.

High red sensitivity and low blue sensitivity of a meter cell, compared to the sensitivity of panchromatic film, can cause a difference in density of negatives exposed outdoors and indoors because of the difference in the color temperature of the light sources. To further complicate this matter, film may not have exactly the same speed with the two types of illumination even though only a single speed is published or set for both. The greatest danger of incorrect exposure stemming from poor spectral response, however, occurs when reflected-light meter readings are taken from strongly colored subject areas and when color filters are used over the camera lens with behind-lens meters. With a meter having high red sensitivity, metering through a red filter would lead to underexposure of the film (see Figure 2-25).

A typical angle of acceptance for general-purpose exposure meters is 30 degrees. Some spot meters have an angle of acceptance as small as 1 degree.

Another name for a reflected-light exposure meter is a luminance meter.

Reflected-Light/ Incident-Light Exposure Meters

Strictly speaking, all exposure meters can measure only one thing—the light that falls on the photoelectric cell. By adjusting the angle over which the cell receives light, and by using neutral-density filters that transmit only a desired proportion of the light (or by incorporating a corresponding adjustment in the calibration system), it is possible for the photographer to obtain correct exposure information (a) when the cell is aimed at the subject as a reflected-light meter; (b) when the cell is placed near the subject and aimed at the camera as an incident-light meter; and (c) when the cell is placed behind the lens in a camera where it receives a sample of the image-forming light that falls on or is reflected by the film or sensor.

Reflected-light exposure meters are calibrated to produce the correct exposure when the reading is taken from a medium-tone area. An 18%-reflectance gray card is widely used as an artificial or substitute midtone. Some hand-held reflected-light meters have acceptance angles that are approximately the same as the angle of view of a camera equipped with a normal focal-length lens, which is approximately 53°, although 30° is more typical. The acceptance angle of reflected-light exposure meters is defined as the angle where the response is one-half the on-axis response.*

When a reflected-light meter is aimed at a scene from the camera position, it integrates the light from the scene's various parts and gives an average reading. Such a reading will produce the correct exposure only with scenes that have a balance of light and dark tones around an appropriate midtone. The meter can be moved closer to the subject to make a reading from a single subject area or from a substitute midtone area, such as an 18% gray card. An alternative is to limit the angle of acceptance so a smaller subject area can be measured from the camera position. Spot attachments are available for

*ANSI, General Purpose Photographic Meters (photoelectric type) (PH2.12-1961).

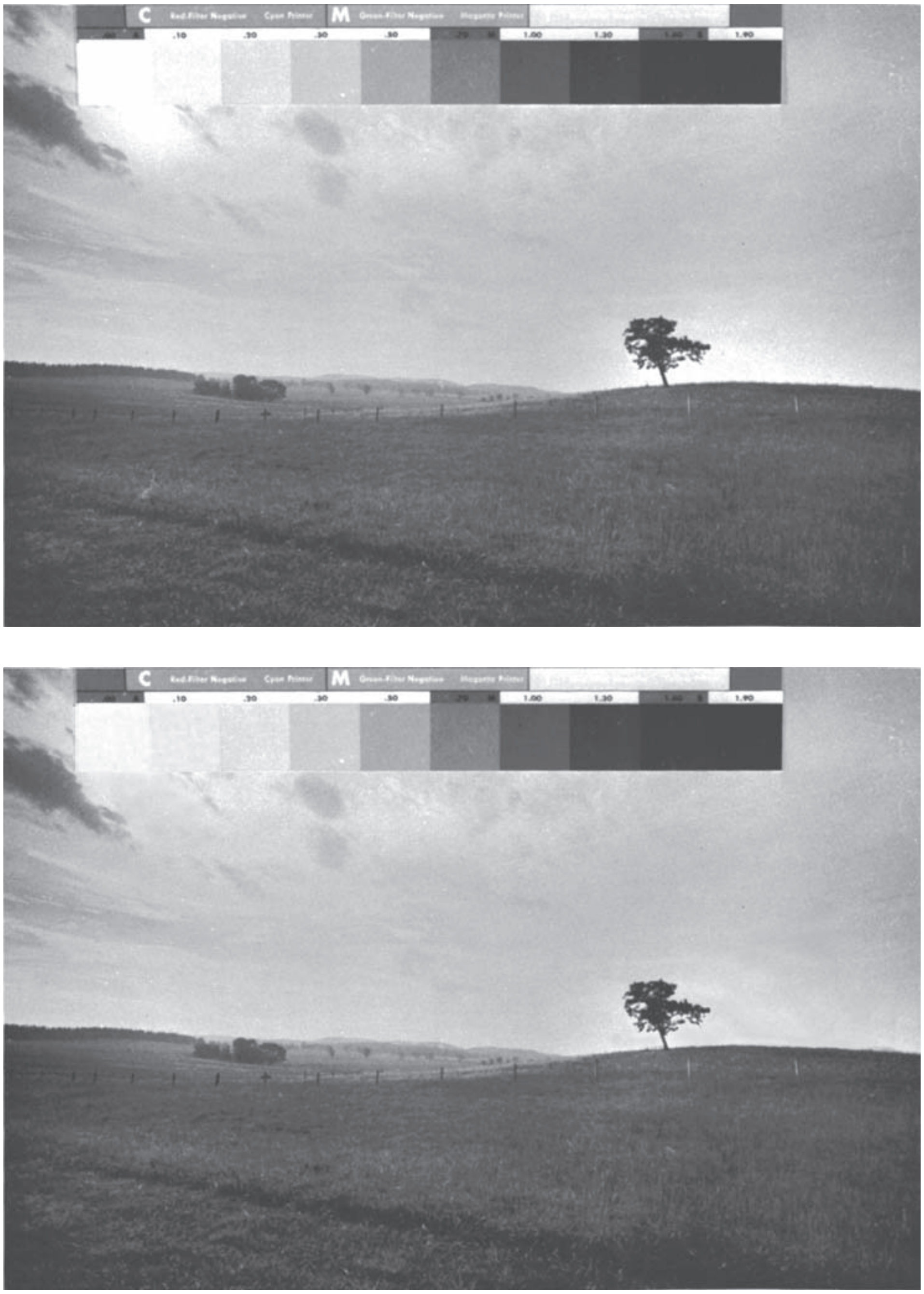

Figure 2-25 Copy photographs of a black-and-white print and gray scale, exposed according to a through-the-lens exposure meter. The top photograph, made with no filter, is correctly exposed. The bottom photograph, made through a red filter, is underexposed because of the high red sensitivity of the cadmium sulfide cell, which produced a false high reading.

some reflected-light meters, and some meters are designed as spot meters with angles of acceptance as small as 1° (see Figure 2-26). Fiber-optic probes are also offered as accessories for some meters, permitting readings to be made from very small areas.

A more appropriate description of a reflected-light exposure meter is *luminance* meter, since such meters are used to measure more than just reflected light such as light transmitted by transparent and translucent objects (such as stained-glass windows) and light

Figure 2-26 The white circle on the post on the right represents the approximate area measured with a 1° spot meter on a photograph made with a normal focal length lens where the angle of view is approximately 53°. (Photograph by (Professor Stephen J. Diehl, Imaging and Photographic Technology, Rochester Institute of Technology.)

emitted by objects (such as night advertising signs and molten metal). Also, some persons prefer to use the term *light* meter rather than exposure meter, but the terms reflected-light meter and exposure meter have become entrenched in the photographic vocabulary through common usage. Actually, since the spectral response curves of exposure meters do not (and should not) match the spectral response curve of the standard observer, the meters do not truly measure light.

Behind-lens meters also can be designed either to integrate the light over a large angle to provide an average reading, or to measure the light from smaller areas. Some cameras have *center-weighted* meter systems, others measure off-center areas. A newer type of metering called evaluative metering is available in most brands of digital SLR cameras, although every manufacturer has a unique name for it. This type of metering will break the scene up into zones and used built in software to analyze the scene and provide an appropriate reading (see Figure 2-27).

If a hand exposure meter is to be used for both reflected-light and incident-light readings, an adjustment must be made when the meter is turned around so that the cell is receiving the higher level of light falling on the subject rather than just the 18% that is reflected from a typical scene. Dividing 100% by 18% produces a ratio of approximately 5.6:1. Therefore, a neutral-density filter that transmits 1/5.6th of the light, placed over the cell, would convert the reflected-light meter to an incident-light meter that would produce the same exposure with a subject that reflects 18% of the incident light (see Figure 2-28). This is typically done with a white translucent dome that is placed over the meter sensor when taking incident readings.

It is appropriate to use a flat receptor on incident-light meters that are

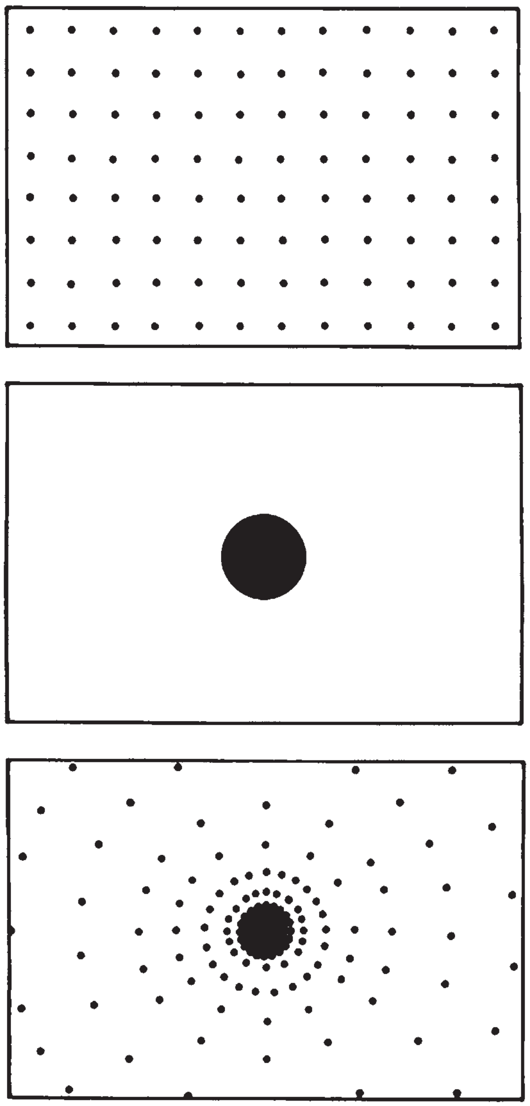

Figure 2-27 The three most popular distributions of exposure-meter sensitivity within the picture area in 35-mm single-lens reflex cameras are averaging (top), spot (middle), and center-weighted (bottom).

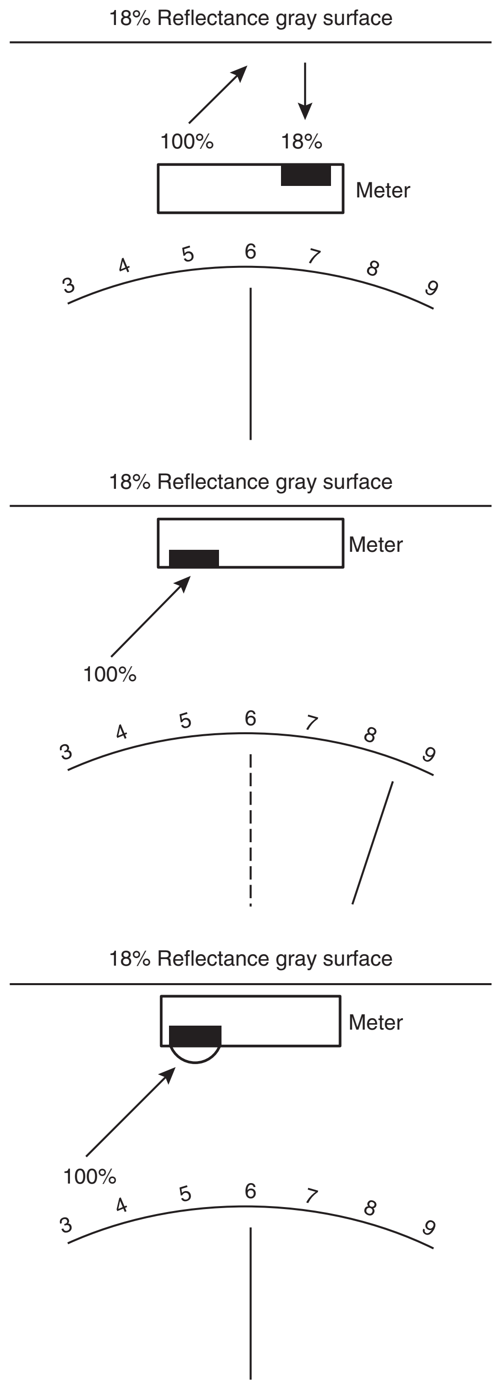

Figure 2-28 Conversion of a reflected-light exposure meter to an incident-light exposure meter. (Top) A reflected-light exposure meter measures 18% of the incident light reflected from a subject of average reflectance. (Middle) A reflected-light exposure meter used as an incident-light exposure meter, without modification, measures 100% of the incident light and produces a false high reading. (Bottom) Adding a diffuser that transmits 18% of the incident light produces the same correct reading as that obtained with the reflected-light exposure meter.

to be used for photographic copying, so that the illuminance will vary on the meter cell and the flat original exactly the same when the direction of the lighting changes. Such a meter is identified as a cosine-corrected meter because the cosine law of illumination states that illuminance changes in proportion to the trigonometric cosine of the angle between the light path and a perpendicular to the surface. Copying lights are typically placed at an angle of 45° on both sides of the

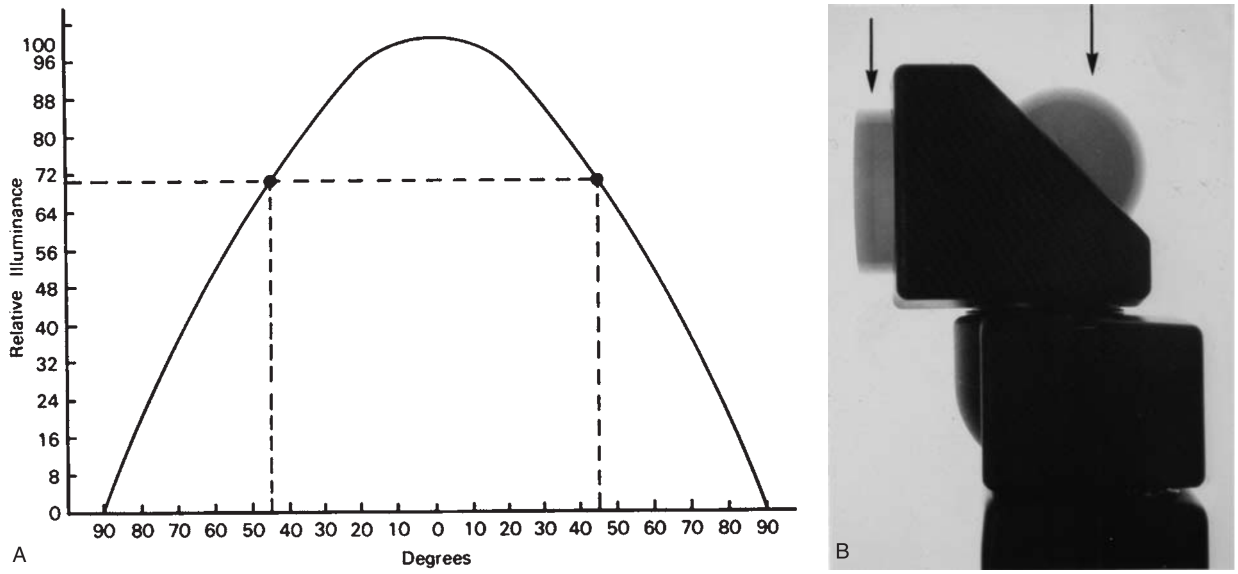

Figure 2-29 The cosine law of illumination (A) the illuminance for light falling on a flat surface varies with the cosine angle of incidence, the relationship represented by the solid curve. The dashed line indicates the relative illuminance for 45° copy lighting. (B) Both flat (cosine-corrected) and hemispherical diffusers are provided with this exposure meter.

stand rather than near the camera, to avoid glare reflections. The cosine of 45° is approximately 0.7, which means the illuminance on the original and the cosine-corrected meter cell will be only 0.7 what it would be if the lights were placed directly in front of the original on the lens axis at the same distance (see Figure 2-29).

Some general-purpose exposure meters provide a flat diffuser to place over the cell that transmits the proportion of light needed to convert the meter to an incident-light meter, as well as to provide cosine-corrected readings for copying purposes. Since the cosine of 90° is zero, flat receptors could not be used with sidelit and backlit three-dimensional subjects and scenes with the meter aimed at the camera. Such a meter could be aimed at the key light provided that a suitable adjustment is made, with a calculator dial, for example, to compensate for the change in effectiveness of the illumination, from 100% for front lighting to 50% for 90° side lighting to 0% for 180° back lighting.

Flat diffusers are recommended for incident-light exposure meters for copying work, and hemispherical diffusers are recommended for photographing three-dimensional subjects.

In 1940, however, Don Norwood introduced a more satisfactory solution—an incident-light exposure meter with a hemispherical diffuser over the cell that automatically compensated for changes in the direction of the key light with the meter aimed at the camera.[3] The Norwood exposure meter operated on the principle that as the key light was moved toward the side from a front-lighted position, it illuminated less and less of the hemispherical diffuser, producing proportionally lower readings. With 90° side lighting, for example, the key light illuminated half the diffuser, and the illuminance reading was 50% of the front-lighted reading—the equivalent of a one-stop change in the camera exposure settings (see Figure 2-30). Today almost all meter manufacturers have adopted the hemispherical diffuser for incident-light exposure meters intended for use with three-dimensional subjects and scenes.

[3] Norwood, "Light Measurement for Exposure Control." *Journal of the SMPTE*, Vol. 54 (1950), pp. 585–602.

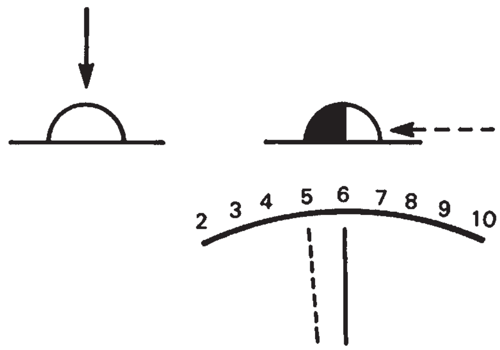

Figure 2-30 Front lighting and 90° side lighting of a hemispherical diffuser, resulting in a one-stop decrease in the meter reading.

With some, however, care must be taken in positioning the meter so that the meter body does not shield the diffuser from the key light in backlit situations.

Meter Scales

Early photoelectric exposure meters were commonly calibrated in photometric units, such as footcandles for illuminance and candelas per square foot for luminance readings, or in numbers that represented relative photometric units. The numbers on these meters formed ratio scales such as 1-2-4-8-16, etc., so that each higher number represented a doubling of the light, or the equivalent of a one-stop change (see Figure 2-31). Some other types of markings have been used, including *f*-numbers that correspond to whole-stop changes, but most contemporary meters with calibrated scales use a simple interval series of numbers such as 1-2-3-4-5-6, etc., where each higher number again represents a doubling of the light, or a one-stop change (see Figure 2-32).

If the numbers on a meter interval scale are light values in the additive system of photographic exposure (APEX), then the relationship of the four factors involved in camera exposure—*f*-number, exposure time, scene illuminance, and film speed—is expressed as:

Figure 2-31 The numbers on this meter dial are proportional to the amount of light falling on the cell. Since each number is double the next lower number, the numbers form a ratio scale.

Figure 2-32 Even though the numbers on this meter dial form an interval scale with equal increments of 1, each number represents double the amount of light of the next lower number.

$$\begin{bmatrix}\text{Aperture value} + \\ \text{Time value}\end{bmatrix} = \begin{bmatrix}\text{Light value} + \\ \text{Speed value}\end{bmatrix}$$

$$= \text{Exposure value or}$$

$$A_V + T_V = L_L + S_V = E_V \quad \text{(Eq. 2-3)}$$

An average outdoor scene has a luminance ratio of approximately 128:1, or a luminance range of approximately seven stops.

The *f*/16 rule can be used as one check on the accuracy of an exposure meter. A meter also can be checked against other meters with a standard light source.

For example with a meter reading light value of 5 (30 foot-lamberts) and a film speed value of 5 (ISO 100) the exposure value is 5 + 5 or 10. Therefore, any combination of aperture and time values that adds up to 10 can be used, such as an aperture value of 3 (*f*/2.8) and a time value of 7 (1/125 second). The values for other *f*-numbers, exposure times, film speeds, and scene illuminance readings are given in Table 2-3. Most interval-scale meters use an arbitrary set of numbers beginning with 1 for the lowest mark on the scale rather than using APEX light-value numbers, but some do include exposure value (E_v) numbers—a combination of light values (L_v) and film-speed values (S_v)—on the calculator dial or elsewhere.

Light Ratios

Because exposure meter readings are commonly used to determine lighting ratios and scene luminance ranges or ratios, it is important to understand the difference between ratio (1-2-4-8) scales and interval (1-2-3-4) scales on meters and to be able to use either. With a ratio-scale meter, the scene luminance ratio can be determined by taking reflected-light readings from the highlight and shadow areas and dividing the larger number by the smaller. For example, 256 (highlight) divided by 2 (shadow) is 128, or a luminance ratio of 128:1. Similarly, the lighting ratio for a studio portrait can be determined by taking an incident-light or a reflected-light reading for the key or main light plus the fill light and a second reading for the fill light alone, so that readings of 60 and 15, for example, represent a 4:1 lighting ratio. A comparison of shadow and highlight reflected-light readings is shown below for the two types of scales:

1-	<u>2</u>-	4-	8-	16-	32-	64-	128 -	<u>256</u>-	512
1-	<u>2</u>-	3-	4-	5-	6-	7-	8-	<u>9</u>-	10
	S							*H*	

There are several methods for determining the lighting ratios. The 128:1 luminance ratio scene on the ratio scale can most be expressed as a 7-stop (9 – 2) scene on the interval scale. Seven stops can be converted to a 128:1 ratio by raising 2 to the seventh power, 2^7 (i.e., $2 \times 2 \times 2 \times 2 \times 2 \times 2 \times 2$) = 128. (Using logarithms, $7 \times \log 2 = 7 \times 0.3 = 2.1$, and the antilog of 2.1 is approximately 128.)

Table 2-3 Conversion formulas and data for the aperture value, time value, light value, and speed value in the additive system of photographic exposure (APEX)

$A_v = \text{Log}_2\,(F\text{–}N)2$	A_v	0	1	2	3	4	5	6	7	8	9	10	
	F-N	1	1.4	2	2.8	4	5.6	8	11	16	22	32	
$T_v = Log_2 1/T$	T_v	0	1	2	3	4	5	6	7	8	9	10	
	T	1	½	¼	1/8	1/15	1/30	1/60	1/125	1/125	1/500	1/1000	Second
$B_v = Log_2 B/6$	B_v	0	1	2	3	4	5	6	7	8	9	10	
	B	6	12	25	50	100	200	400	800	1600	3100	6400	Footcandles
$S_v = Log_2 S/3$	S_v	0	1	2	3	4	5	6	7	8	9	10	
	S	3	6	12	25	50	100	200	400	800	1600	3200 (Arithmetic)	ASA/ISO

Meter Accuracy and Testing

Variability tells us that we cannot assume all exposure meters are accurate, even when they are new. We know variability affects all aspects of the photographic process, including different exposure meters produced by the same manufacturer that are supposed to be identical. The issue is whether the variability is small enough so that it can be ignored or whether some compensation should be made. How much error should be tolerated in an exposure meter is not an easy question to answer. In any event, photographers commonly test their new meters against other meters of known performance, and professional photographers usually feel insecure unless they have more than one meter in their possession at all times.

Calibrated light sources are available for testing exposure meters and other light meters, but their high cost usually keeps individual photographers from owning one, although they are used by manufacturers and testing laboratories. Sunlight can be used as a standard light source, however factors that can affect the illuminance, such as time of day and sky conditions must be accounted for. If you only want to make a comparison between exposure meters, for example a new meter and one of known performance, a light source only needs to be constant and does not need to be calibrated. A transparency illuminator works quite well for comparing exposure meters. The meter should be placed against the center of the illuminator, which will eliminate variability because of differences in angle of acceptance, distance from the light source, and shadows of the meters (see Figure 2-33).

The frequency histogram in Figure 2-34 shows the result of a comparison of approximately 200 new and used exposure meters of various brands. All meters were set at the same ISO, and the indicated exposure times for a relative aperture of *f*/16 were recorded. The total range of exposure times corresponds to a ratio of approximately 16:1 or four stops. Ninety percent of the readings fell within a 2:1 ratio, or a one-stop range. Since all of the meters that had zero settings were properly zeroed, the only method of compensating automatically for consistently high or consistently low readings is to make an adjustment in the ISO setting. Thus if a meter reads one stop too high, it should be set for one-half the published ISO speed.

An alternative method for testing an exposure meter is to capture an image at the settings indicated by the meter. Additional images are taken by bracketing the original indicated exposure by 1/3 or 1/2 stops which both overexposes and underexposes the image. The photographer would then determine which image had the best

Figure 2-33 A transparency illuminator being used as a standard light source to check the calibration of an exposure meter.

Reflected-light exposure meters are calibrated for midtone readings.

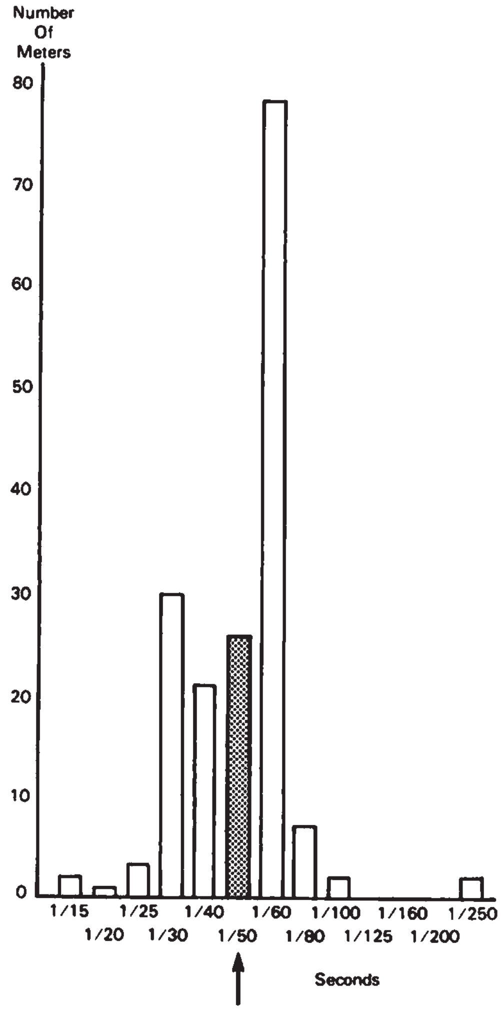

Figure 2-34 Frequency histogram showing the results of the testing of approximately 200 exposure meters on a standard light source. Although the variability represents a range of four stops, 90% of the meters fell within a one-stop range.

exposure and compensate the meter readings accordingly. Photographers sometime refer to this testing process as deriving a personalized exposure index. There are many factors that can affect these results such as shutter accuracy and efficiency, flare, lens transmittance, color temperature of the light source and if using film development and reciprocity law failure. Because of this the photographer should not rely on a single set of images to determine meter accuracy.

Compensation can be made for an exposure meter that reads consistently high or low by adjusting the ISO setting.

Methods of Using Reflected-Light Exposure Meters

Not only do photographers have a choice between reflected-light and incident-light exposure-meter readings, but they also have a choice of various types of reflected-light readings. The types of reflected-light readings that will be considered here are midtone, Keytone and Zone System, calculated midtone, camera position, and behind-lens camera meter readings.

Midtone Readings

Film speeds for conventional black-and-white films are based on a point on the toe of the characteristic curve where the density is 0.1 above base-plus-fog density, which corresponds to the darkest area in a scene where detail is desired. Exposure-meter manufacturers, on the other hand, calibrate the exposure meter to produce the best results when reflected-light readings are taken from midtone areas. Meter users who are not happy with this arrangement can make an exposure adjustment (or, in effect, recalibrate the meter) so that the correct exposure is obtained when the reflected-light reading is taken from the darkest area of the scene—or the lightest area, or any area between these two extremes. This type of control is part of the *Keytone* method and the *Zone System*.

Reflected-light meters are calibrated for midtone readings, therefore any area used for a reflected-light reading will be reproduced as a midtone, even if the area is the lightest or darkest area in the scene, if no adjustment is made. For example, if a reflected-light reading is taken from a white subject, this will cause the white subject to be recorded as a medium-tone, which is considerably darker than it would be

if it were correctly exposed. If we were using film, the negative will be underexposed. In terms of the film characteristic curve, all of the tones will be moved to the left on the log exposure axis, causing the midtone of the scene to move from the straight line down onto the toe, and the shadows to move from the toe onto the base-plus-fog part of the curve where detail will be lost. In a digital system this would cause the image brightness histogram to shift to the left causing shadow information to be clipped to zero.

A typical white surface reflects about 90% of the incident light, which is five times as much as is reflected from an 18%-reflectance gray card, so that taking the reading from a white area causes an underexposure by a factor of five, or a little more than two stops. With the negative-positive process this underexposed negative still can be printed so that the white area from which the reading was taken appears white; but the loss of contrast, and especially the loss of detail in the darker areas, cannot be fully corrected. With reversal color films where the slide or transparency is the end product, and with instant or one-step picture materials that produce prints directly, taking a reflected-light reading from a white area again reproduces that area as a medium tone—which now is denser than it would be with normal exposure. Since such reversal materials have little exposure latitude, they are especially useful for demonstrating the differences in results of the various methods of using exposure meters.

The photographs in Figure 2-35 illustrate the results when reflected-light readings are taken from a midtone area, a light area, and a dark area. Note that the areas from which the readings were taken are all reproduced as the same medium density but that the overall effect is satisfactory only when the reading was taken from the midtone area.

One of the problems with the midtone reflected-light method is the difficulty of selecting an appropriate medium-tone area to take the reading. If we think in terms of a copying situation in which the subject tones range from white to black, as in a gray scale, a gray that appears to be midway between white and black will have a reflectance of about 18%, or a density of about 0.74 (see Figure 2-36).

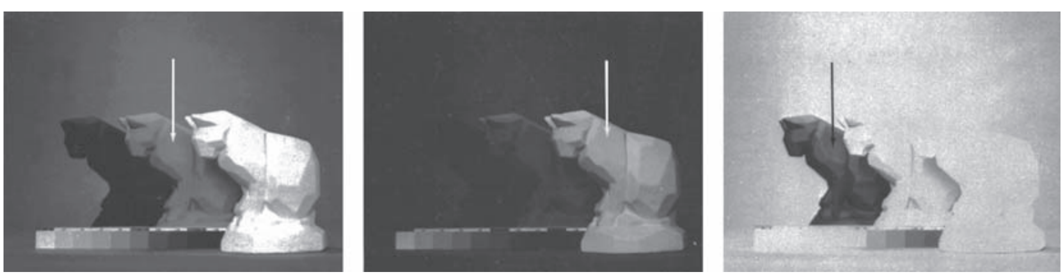

Figure 2-35 Reflected-light exposure meter readings. (Left) The black-and-white plaster cats correspond in reflectance to the two ends of a gray scale; the gray cat represents a midtone. A reflected-light meter reading from the gray cat reproduces it as a realistic medium gray and produces the best exposure for the entire scene. In the original Polaroid print, there is tonal separation of all ten steps in the gray scale and detail in the front planes of all three cats—although not in the shadow underside of the black cat or the rim-lighted top edge of the white cat. (Middle) A reflected-light reading from the white cat results in its being reproduced as a medium gray rather than white, and the photograph as a whole is underexposed. (Right) A reflected-light reading from the black cat results in its being reproduced as a medium gray rather than black, and the photograph as a whole is overexposed.

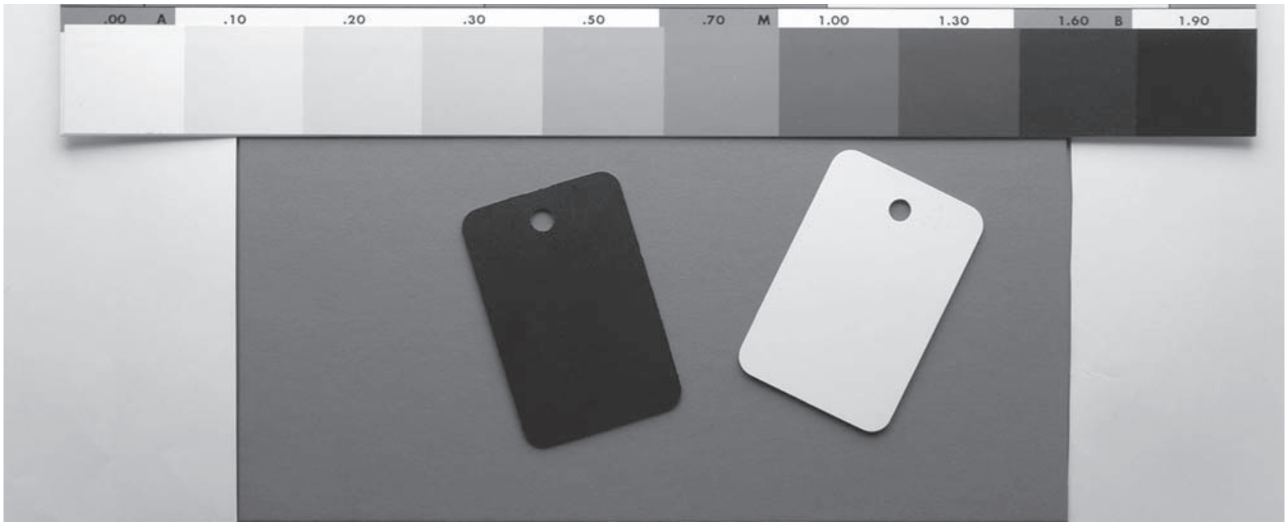

Figure 2-36 A gray surface with a reflectance of 18%, or a reflection density of about 0.74, is perceived as being midway between white and black in lightness and serves as an appropriate photographic midtone.

Taking a reflected-light meter reading from a light area, without adjustment, results in underexposure.

Detail can be obtained in a shadow area by taking a reflected-light reading in that area and decreasing the indicated exposure by four stops.

Since the photographic midtone agrees with the visual midtone, it is appropriate to use an 18%-reflectance gray card as an artificial midtone—such neutral test cards are made for this purpose. In copying situations, the neutral test card should be positioned parallel to the original so that the change in illuminance with the angle of the light, as specified by the cosine law of illumination, is the same on the original and the test card.

A neutral test card can be used as an artificial midtone with three-dimensional subjects as well, provided the card is now aimed midway between the camera and the dominant light source rather than directly at the camera (see Figure 2-37). Neutral test cards have a fairly dull surface, however care must be used when taking reflected-light meter readings so that the angle of the meter avoids glare reflections from the light source. The meter should be positioned close enough to the card to avoid including any areas behind the card in the reading, but not so close as to cast a shadow onto the card. Spot attachments or spot meters make it possible to obtain accurate readings at a greater distance than with conventional reflected-light meter to avoid this problem.

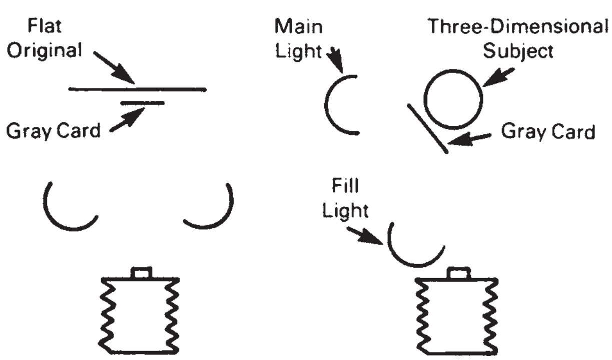

Figure 2-37 In copying setups, the gray card should be positioned parallel to the original. With three-dimensional subjects the gray card should be angled midway between the main light and the camera.

Keytone and Zone System Readings

White-card film speeds were commonly provided on film data sheets in addition to the conventional film speeds in past years, and are still provided for some films designed especially for copying. Since a typical white surface reflects about 90% of the light, or five times as much as the 18%-reflectance neutral test card, the white-card film speed would be only one-fifth the gray-card film speed with arithmetic film speeds.

Reasons for using a white-card exposure meter reading in preference to a gray-card reading are that white surfaces are more readily available than 18%-reflectance gray surfaces, and in low light levels it might be possible to obtain a white-card reading when an exposure meter is not sufficiently sensitive to obtain a reading from a gray card. An alternative to changing the ISO setting on the exposure meter for white-card readings is to place a marker in the appropriate position on the meter calculator dial and then set that marker rather than the normal marker opposite the meter reading.

When it is especially important to retain shadow detail in a photograph, the *Keytone* method can be used whereby a reflected-light meter reading is taken from the shadow area and an appropriate mark is made on the calculator dial opposite that reading. (If no adjustment were made, the shadow area would be reproduced as a medium tone, and the negative overall would be much too dense.) The original Weston exposure meter had a U-position or shadow marker four stops below the normal arrow. The same effect can be obtained with any reflected-light exposure meter by reading the shadow area and then giving the film one-sixteenth the exposure or four stops less exposure than that indicated by the normal marker.

A logical extension of the Keytone method, beyond calibrating the calculator dial for white-card or highlight readings and for shadow readings, is to calibrate it for each stop between these limits. Such a calibration is an important part of the *Zone System*, whereby eight neutral patches with increasing densities from white to black are associated with the seven-stop range on the meter dial that represents a normal scene having a luminance ratio of about 1:128. The lightest and darkest patches represent the useful density range of the printing paper, and each patch indicates the predicted density on the print for the corresponding luminance value in the scene.

The photographer, however, is not limited to striving for a faithful tone reproduction with Keytone and Zone System readings. If, for example, the photographer wants to depict snow somewhat darker than normal to emphasize the texture, the patch having the desired density is placed opposite the meter reading from the snow. This procedure is especially useful when using color transparency film in which the transparency is the end product, and therefore printing controls are not available (see Figure 2-38).

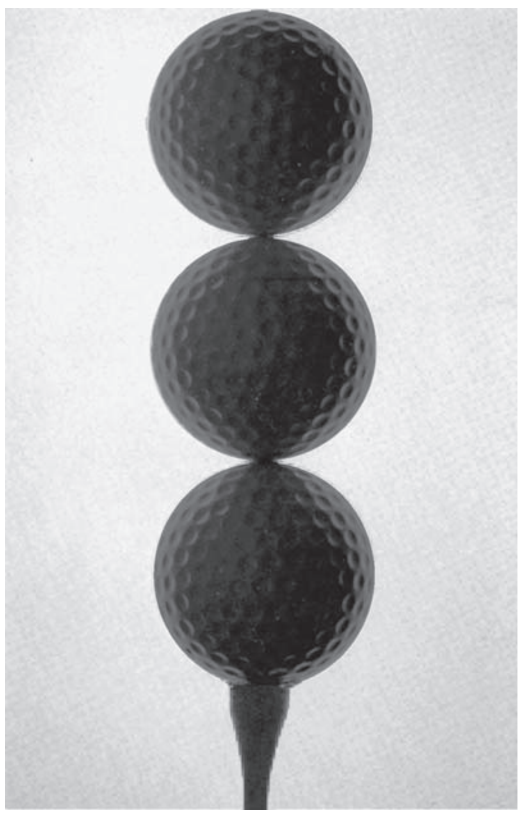

Figure 2-38 Silhouettes and semi-silhouettes are dramatic examples of situations in which facsimile tone reproduction is not the objective, as with this photograph of white golf balls. With the Zone System, the photographer can determine the reproduction tone for a given subject area at the time the film is exposed.

Adjusting film development to compensate for high-contrast and low-contrast scenes is also an important feature of the Zone System.

Calculated Midtone Readings

In practice, it is often difficult to visually scan a scene and subjectively select an appropriate midtone area to take a reflected-light exposure meter reading. The scene may contain light and dark tones but no midtones, and even if there is an appropriate midtone area, it may be difficult to identify because of the influence of the colors of objects, an imbalance in the size of light and dark areas, local brightness adaptation of the visual system, and other factors. An objective method for locating a midtone reading is to take separate readings from the lightest and darkest areas where detail is desired and to select a middle value.

Calculated midtone reflected-light exposure meter readings can be obtained by averaging highlight and shadow readings.

Some care is necessary because the middle value is not an arithmetic average of the highlight and shadow luminances. The scales on most hand meters are set up so that each higher major marking and number represents a doubling of the luminance, or the equivalent of a one-stop change. If the meter has an interval scale of numbers (1-2-3-4-5-6-7), and if the shadow reading is 1 and the highlight reading is 7, the *calculated midtone* value is the middle number, 4. With such interval scales, the same midtone value is obtained by adding the highlight and shadow values and dividing by 2—for example,

$$\frac{(7+1)}{2} = 4$$

If the meter has a ratio scale of numbers (1-2-4-8-16-32-64), and the shadow reading is 1 and the highlight reading 64, the calculated midtone value is again the middle number, in this example 8. Calculating the midtone value by averaging the shadow and highlight readings with the ratio scale will result in a large error since the average of 1 and 64 is 32.5, not 8.

No change in procedure is required for hand meters or behind-lens meters that read directly in *f*-numbers (for a given shutter speed) or in shutter speeds (for a given *f*-number), since both scales are ratio. A correct midtone value is obtained by taking a shadow reading and a highlight reading and selecting the middle number on the *f*-number or shutter-speed scale (see Figure 2-39).

A bonus of the calculated-midtone method is that by taking readings in the darkest and lightest areas where detail is desired, it is easy to determine whether or not the scene is normal in contrast. The original Weston exposure meter had shadow and highlight markings on the calculator dial to indicate that the luminance ratio for an average scene is 1:128 (or a luminance range of seven stops or seven zones). Later studies suggested a slightly higher ratio of 1:160, which still rounds off to seven stops in terms of whole stops.

Aperture		Shutter Speed
f/2.8	SHADOW	1/8 sec.
f/4		1/15
f/5.6		1/30
f/8	MIDTONE	1/60
f/11		1/125
f/16		1/250
f/22	HIGHLIGHT	1/500

Figure 2-39 The calculated midtone is found with a shutter-priority system (left) by noting the *f*-number that is midway between the *f*-numbers indicated for a shadow reading and a highlight reading. With an aperture-priority system (right) the shutter speed midway between the indicated speeds for shadow and highlight readings is selected.

Various options are open to the photographer if, for example, a scene is discovered to have considerably more contrast than the average scene:

1. By adjusting the exposure, detail can be retained in either the highlights or the shadows by sacrificing detail in the other areas.
2. In some situations, it is possible to reduce the luminance ratio with a fill light or a reflector; in this case, the midtone value should be recalculated.
3. For negative films, contrast can be lowered by reducing the development time so that the negative will print on normal-contrast paper. Since the effective film speed varies with the degree of development, it is necessary to make an adjustment in the film speed or the exposure.
4. Since conventional negative-type films have more exposure latitude than required for an average scene, the contrast adjustment can be postponed to the printing stage. The excess latitude is mostly on the overexposed side, however, so an exposure adjustment may be required to retain shadow detail.
5. With reversal-type color films, contrast can be reduced with controlled flashing. Some slide copiers are designed to provide this option. The same effect can be achieved with any camera by giving the film a second exposure, using an out-of-focus image of a gray card and an appropriate reduction of the exposure.

Other terms applied to exposure methods that are similar or identical in concept to the calculated-midtone method are *brightness-range, luminance-range, luminance-ratio*, and *log luminance-range*.

Camera-Position Readings

The *camera-position* or *integrated-light* metering method consists of aiming a reflected-light exposure meter at the scene from the camera position. Assuming that the meter's angle of acceptance is about the same as the angle of view of the camera-lens combination, the meter provides a single reading that represents an average of all the luminances of the different subject areas being included in the photograph. Correct exposures should result with scenes that are well balanced with respect to light and dark areas. Scenes in which light areas are dominant produce false high readings, which lead to underexposure. Scenes in which dark tones prevail produce false low readings and overexposure (see Figure 2-40).

The success of camera-position reflected-light readings depends upon a reasonable balance of light and dark tones in the scene being photographed.

Scenes in which light areas dominate produce false high readings, which lead to underexposure. Scenes in which dark tones prevail produce false low readings and overexposure.

A large proportion of photographs made using this method are satisfactory because most of the scenes photographed are reasonably well balanced in light and dark areas or because of the exposure latitude of the film or sensor. It is not difficult to recognize scenes that deviate dramatically from a balance of light and dark areas, where corrective action should be taken. Also, exposure-meter instruction manuals usually caution the user to tilt the meter downward to avoid including bright sky areas in outdoor meter readings.

Camera Meters

Although selenium-cell photovoltaic-type exposure meters have been built into small-format cameras, the introduction of the more sensitive cadmium sulfide cell and other meters of the photoconductive type made it possible to reduce the cells to a more appropriate size. With the development of small

No compensation is required for the increased lens-to-film distance for close-ups with behind-lens exposure meters

Figure 2-40 Camera-position reflected-light readings. (Top left) Camera-position reflected-light exposure meter readings produce the best results with scenes that are balanced in light and dark tones. (Photograph by Derrick Clark.) (Bottom) Predominately light scenes produce inflated meter readings, which produce underexposure. (Photograph by Derrick Clark.) (Top right) Dark scenes produce false low readings, which produce overexposure. (Photograph by David Filiberti.) (David and Derrick are both Advertising Photography students, Rochester Institute of Technology.)

cells, camera meters were moved from being mounted on the front surface of the camera to behind the lens of the camera. Meters with surface-mounted cells perform in a manner similar to that of a reflected-light hand meter, that is, aimed at the subject from the camera position to make an integrated-light reading.

Considering only small-format cameras, behind-lens meters are better suited to focal-plane shutter cameras than to cameras having between-the-lens shutters that are open only when the film is being exposed. There has been considerable experimentation with the location, size, and shape of the behind-lens cell or cells. Cells have been placed in various positions on the prism of single-lens-reflex cameras, on the mirror, behind the mirror, and off to one side where the cells receive and measure light reflected from a mirror or beam splitter, the shutter curtain, or even the film itself (see Figure 2-41).

Many technical problems had to be solved with behind-lens meters, such as preventing light that enters the viewfinder from behind the camera from reaching the cell, preventing polarization of the image light being measured (which would give inaccurate readings when a polarizing filter is placed on the camera lens), and compensating for the change in the size of the diaphragm opening between the time the light is measured and when the exposure is made. There are also many variations concerning the size, shape, and location of the picture area being measured, including integrated, center-weighted, off-center weighted, spot, and multiple cells.

Although behind-lens meters generally offer less precision with respect to measuring the light from selected parts of a scene and are restricted to reflected-light-type readings, they offer certain advantages over handheld meters in addition to convenience. Behind-lens meters essentially measure the light falling on the image sensor, variations in the light caused by increasing the lens-to-image sensor distance for close-up photography, flare light, and variations in transmittance of different lenses set at the same *f*-number are automatically compensated for. Some camera manufacturers also claim that their meters compensate for the absorption of light by color filters placed over the lens. If a film camera

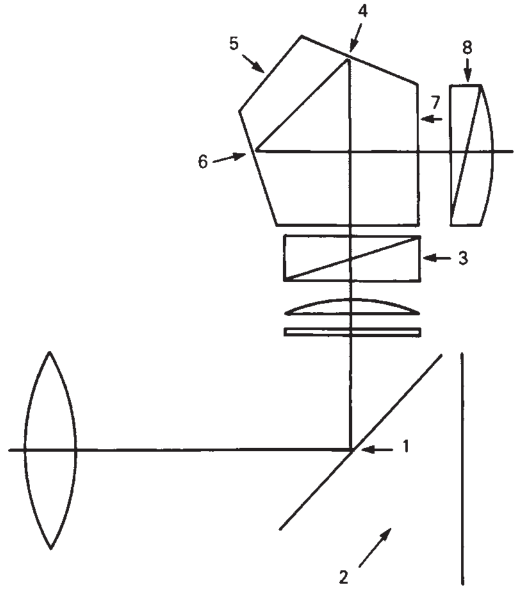

Figure 2-41 A variety of positions have been used for the exposure-meter cell in single-lens reflex cameras by different manufacturers.

1. Behind the mirror. Measures direct light from the lens through clear lines or partially transmitting mirror.
2. Behind the mirror. Measures light reflected from the film or sensor during the exposure.
3. Between the focusing screen and the pentaprism. Measures light diverted by a beam-splitter.

4–7. On the pentaprism.

8. On the eyepiece. Measures light diverted by a beam-splitter. Difficulties of behind-the-lens metering can include inflated readings due to light entering the eyepiece from the rear, false readings with polarizing filters due to polarization of light by the metering system, and inconsistencies in diverting a fixed proportion of light to the meter cell.

is being used with panchromatic film, caution should be used here. The spectral response of the meter cells may not be in close agreement with the spectral sensitivity of the panchromatic film, which may cause a metering error. There is currently no such data available for digital cameras. Color filters may, however, produce unpredictable results when interacting with the white balancing software of the camera. Experimenting with your camera is recommended here.

Incident-Light Readings

Incident-light meter readings have long been popular with professional motion-picture and still photographers because they can be made quickly and they give dependable results. The basic instructions for using an incident-light exposure meter is to hold the meter in front of the subject and aim it at the camera. This eliminates the need to decide if the scene has an equal balance of light and dark areas because the meter measures the light falling on the subject rather than the light reflected by the subject, and the meter is calibrated for a subject having a range of tones from black to white with a medium tone of 18% reflectance. Considering the placement of the position of the dominant light source is also eliminated with incident-light meters having hemispherical diffusers because this compensates for changes in the direction of the light and the corresponding change in the relative sizes of highlight and shadow areas.

Instruction manuals for exposure meters sometimes warn the user that the meter can only measure light, it can't think for the photographer; this applies to incident-light as well as reflected-light exposure meters. One potential source of error is associated with the time-saving observation that when the light falling on the subject and the camera is the same, as when both are in direct sunlight, the reading can be taken at the camera position. It is obvious that when the camera is in the shade of a tree or building and the subject is in direct sunlight, the incident-light reading must be taken in the sunlight—but it is not so obvious, when a light source is close to the subject, that readings can be dramatically different at the subject and one foot in front of the subject. Therefore, the closer the light source is to the subject, the more important it is to take the incident-light meter reading as close to the subject as possible. The inverse-square law of illumination can be ignored with sunlight because of the great distance of the sun, but it should not be ignored indoors when a light source is within a few yards of the subject.

Although the point has already been made that it is not necessary to consider the balance of light and dark areas in a scene for incident-light readings, it is advisable to modify the exposure indicated by an incident-light meter when the main subject is either very light or very dark in tone. It is advisable to increase the exposure by one-half to one stop with black or very dark objects and to decrease the exposure by one-half to one stop with white or very light objects. Since it is possible to hold detail in an entire gray scale or a scene containing both white and black areas, even with reversal color films, which have limited exposure latitude, it is necessary to explain why the exposure should be adjusted when the subject is predominantly light or dark.

The best illustration of the principles at work here is with the characteristic

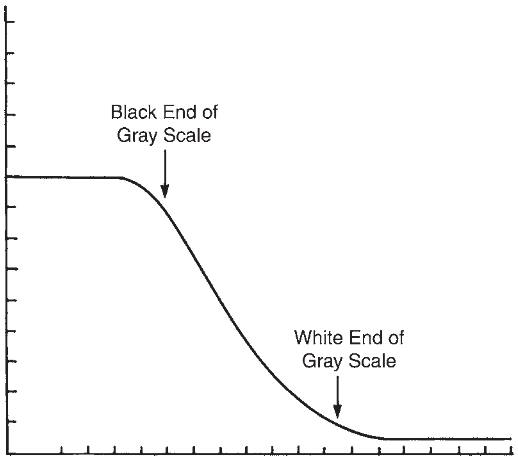

Figure 2-42 Since the white and black ends of a gray scale photographed on reversal-type film fall on the shoulder and toe of the characteristic curve where the slope is lower, some contrast is lost in both of these areas compared to the intermediate tones, which fall on the steeper central part of the curve.

curve for a reversal-type film shown in Figure 2-42; it will be noted that the white end of a correctly exposed gray scale falls on the toe and the black end falls on the shoulder. Some contrast is therefore lost in both of these areas, compared to the intermediate tones, which fall on the central part of the curve. This compression of contrast in the lightest and darkest areas is acceptable when they are not the dominant subject of the scene, but when either becomes the main area of interest it is better to adjust the exposure to move that area onto or closer to the straight line in order to increase the detail and contrast (see Figure 2-43).

Incident-light exposure meters with hemispherical diffusers should be positioned close to the subject and aimed at the camera.

Reflected-light-type exposure meter readings are appropriate for subjects that emit or transmit light rather than reflect light.

Properly made reflected-light meter readings and incident-light meter readings should indicate the same camera exposure settings with normal scenes.

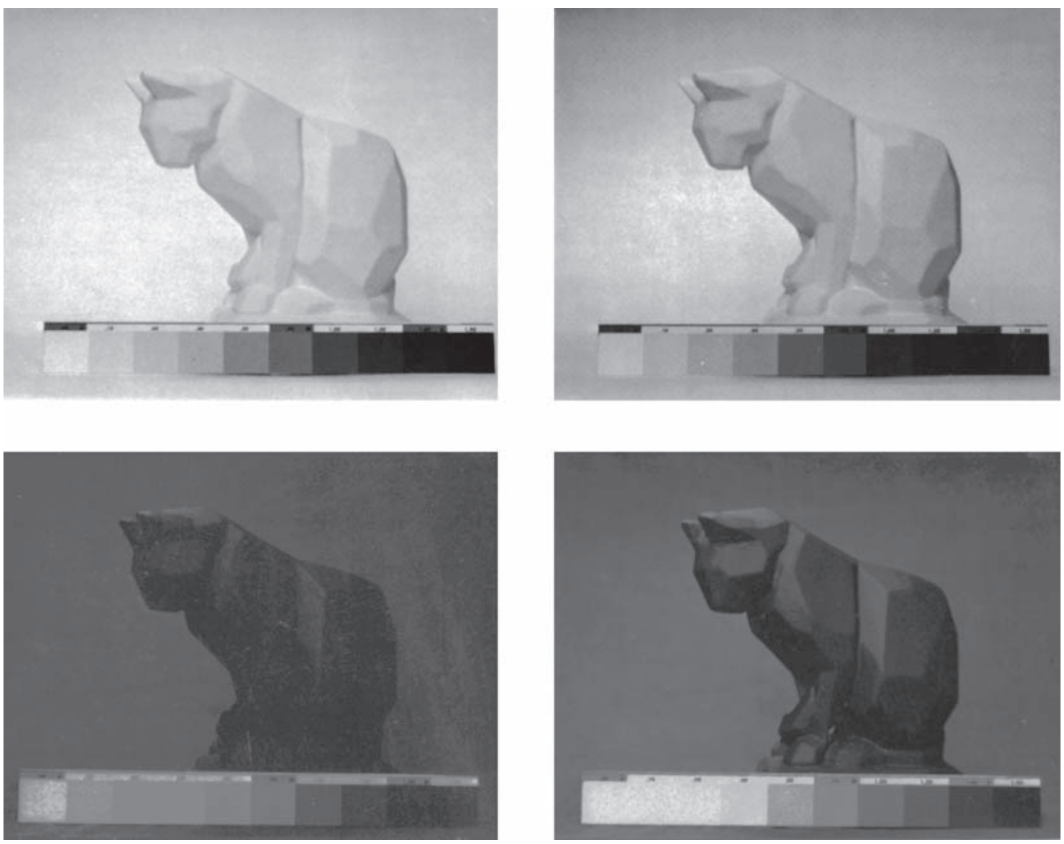

Figure 2-43 Although incident-light meter readings (or reflected-light meter readings from a neutral test card) produce the optimum exposure for subjects having a normal range of tones as represented by a gray scale, exposure adjustments are recommended for high-key scenes and for low-key scenes. (Top left) White object on light background with normal exposure. (Top right) One stop less exposure. (Bottom left) Black object on dark background with normal exposure. (Bottom right) One and one-half stops more exposure.

Figure 2-44 A situation in which it would be difficult to obtain a dependable reflected-light exposure meter reading because of the small size and the predominately light tone of the die. (Photograph by James Craven, Imaging and Photographic Technology student, Rochester Institute of Technology.)

A downward adjustment in the film-speed setting is recommended when developing film to a lower-than-normal contrast index.

No single method of using an exposure meter is appropriate for all picture-making situations. Incident-light readings cannot be made when the image-forming light is either emitted or transmitted by the subject rather than being reflected. Examples of emitted light are molten metal, flames, and fluorescent and phosphorescent objects. Transmitted light is encountered when transparent or translucent materials are illuminated from behind, as with stained-glass windows, some night advertising signs, a photographic transparency placed on an illuminator for copying, and sunsets. They also cannot be used when you cannot physically get close to the object being photographed, for example, an animal in the wild.

In some situations, incident-light meter readings are more appropriate than reflected-light readings. Probably the most commonly encountered situation of this type is where the subject or the subject areas are too small to be read accurately even with a narrow-angle spot-type reflected-light meter. This problem occurs not only in the fields of close-up photography and photomacrography but also when photographing a detailed object such as a black line drawing on a white background, where the light and dark tones are not balanced in size and the individual areas are too small to be measured (see Figure 2-44).

In most picture-making situations, the photographer has the choice of making either reflected-light or incident-light exposure meter readings. With meters that are designed to be used in both modes, it is a valuable exercise for the photographer to make comparison readings. When the readings do not agree, comparison photographs will reveal which method is superior in that type of situation. Reflected-light readings from an 18%-reflectance neutral test card are essentially the same as incident-light readings and should consistently indicate the same camera exposure.

Effective Film Speed and Degree of Development

Published film speeds for black-and-white films are based on a specified degree of development. Developing the film to a higher contrast index tends to increase the film's effective speed, up to a limit, and developing to a lower contrast index tends to decrease the effective speed. In practice, it is not uncommon for photographers to develop film to higher and lower contrast indexes than those indicated in the film speed standard.

Film development is sometimes altered to compensate for the difference in printing contrast between condenser

and diffusion enlargers, to compensate for variations in scene contrast, and to compensate for variations in the amount of camera flare light in different situations. Adjustments in the effective film speed can be made either by altering the film-speed setting on the exposure meter, or by using the published film speed and then incorporating the correction in the choice of camera shutter speed and *f*-number settings.

Film manufacturers provide information on the film data sheet regarding adjustments to developing times and concentrations to assist the photographer in achieving the final desired contrast for the film. Film response curves are also provided to show the effect of altering the development on the shadow, midtone, and highlight areas within the negative.

Flash Guide Numbers

Put simply, a flash guide number is a measure of the light output by the flash unit. In the absence of a flash meter, the guide number is used to determine the proper exposure when using a manual flash. Guide number is defined as follows:

$$\text{Guide Number} = f\text{-number} \times \text{flash-to-subject distance} \qquad \text{(Eq. 2-4)}$$

Notice that the equation indicates flash-to-subject distance and not camera-to-subject distance. If the flash is placed in the camera hotshoe the two distances are the same, however if the flash is not on the camera the distance may be different.

The above equation can also be used to determine the proper *f*-number to use (*f*-number = guide number/flash-to-subject distance). The *f*-number calculation may have to be rounded to the nearest available *f*-number. Consider bracketing the exposure to ensure that the results are pleasing. Keep in mind most cameras have only one sync speed when using flash so only the aperture can be adjusted, not the shutter speed in this situation.

Flash guide numbers are provided for an ISO speed of 100. The higher the guide number, the higher the intensity and the greater the flash-to-camera distance can be. Guide numbers can easily be adjusted for different ISO values. The guide number will double for two stops in ISO speed. For example, if the guide number is 80 for an ISO of 100, it will be 160 for an ISO of 400. Guide numbers are often provided in both feet and meters distances, so care should be taken to use the proper units. A guide number of 43 when using meters is the same as 96 when using feet.

Additional complications are encountered in attempting to determine the correct exposure with guide numbers when using bounce flash (where the reflectance of the reflecting surface must be taken into account) and multiple flash (where the cumulative effect of two or more flash sources at different distances and angles, and sometimes different intensities, must be calculated).

Flash Meters

Conventional exposure meters cannot be used with flash and electronic flash because the meters are designed to measure the light from a source of constant intensity rather than a source of rapidly changing intensity and short duration. Electronic-flash meters work on the principle of measuring the total amount of light

Some electronic flash units have built-in sensors that terminate the flash when the system indicates that the film has received the correct exposure.

Figure 2-45 An electronic-flash exposure meter.

that falls on the photocell over an appropriately short period of time by charging a capacitor and then measuring the charge (see Figure 2-45). Some electronic-flash meters have required a sync-cord connection with the flash unit to be able to measure the light from the flash plus ambient light for the approximate period that the camera shutter would be open. Other meters are able to achieve this without a physical connection with the flash unit, and meters are now available that can be used both as a conventional exposure meter and as an electronic-flash meter. Whereas certain electronic-flash meters can be adjusted to integrate the flash plus ambient light over a time interval equal to the selected shutter speed, others operate only over a fixed instantaneous interval, such as 1/60 second.

An alternative to measuring the light from an electronic-flash unit with a preliminary trial flash and a meter is to measure the light reflected from the subject by a sensor built into the flash unit and then terminate the flash when the sensor system indicates the film has received the correct amount of light. The process by which the duration of the flash is shortened to provide the correct exposure is called *quenching*. Early quenching systems achieved the effect by dumping the remaining capacitor charge when sufficient light had been emitted, thus wasting the unused charge and shortening battery life. More recent units have incorporated a means of breaking the circuit between the capacitor and the tube when a signal is received from the metering system, without wasting the remaining charge in the capacitor. When quench-controlled electronic-flash units are used for close-up photography, the flash duration tends to be extremely short. The short duration provides excellent action-stopping capabilities for the photographing of rapidly moving objects—but because of reciprocity effects, the density, contrast, and color balance of the photographic image can be affected (see Figure 2-46).

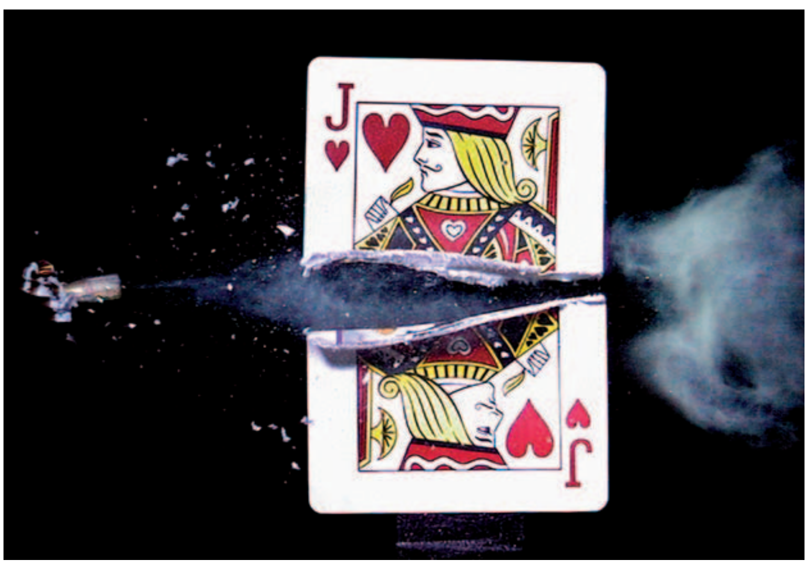

Figure 2-46 A bullet photographed in the process of cutting a playing card in half demonstrates the action-stopping capability of short-duration electronic-flash light sources. (Photograph by Professor Andrew Davidhazy, Imaging and Photographic Technology, Rochester Institute of Technology.)

Color-Temperature Meters

Color-temperature meters are closely related to photoelectric exposure meters, even though they are designed to measure the spectral quality of light rather than the quantity. An ingenious photographer can use a conventional exposure meter as a color-temperature meter by taking readings in sequence through a red filter and a blue filter and setting up a conversion chart or dial based on the relative values of the two readings. One type of color-temperature meter contains two photocells and circuits, with a red filter over one cell and a blue filter over the other, and a calibrated dial to indicate the relative currents in the two circuits in terms of degrees Kelvin or mireds (see Figure 2-46). Modern color-temperature meters typically use three silicon photodiodes that are filtered for red, green, and blue sensitivities that approximate the sensitivity of color film. The meter will measure the amount of energy present in the three regions and determine the color temperature by finding the closest match to a blackbody curve. Meters will either provide a color temperature, a mired shift, or a Wratten filter number to achieve the desired color temperature. These meters are intended to be used with continuous spectral power distributions that approximate a blackbody such as tungsten lamps.

Color-temperature meters operate by comparing the relative amounts of two or three different colors of light in the incident light.

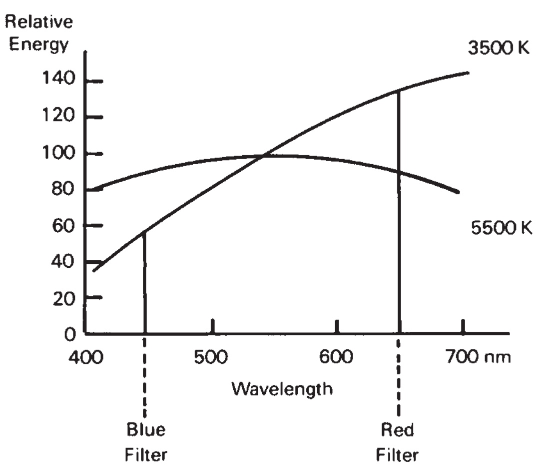

Figure 2-47 In a two-filter color-temperature meter the relative amounts of blue light and red light are measured. The ratio of blue to red is approximately 1:1 for the 5,500 K illumination, but approximately 1:2.4 for the 3,500 K illumination.

REVIEW QUESTIONS

1. Identify the correct formula:
   A. *f*-number = effective aperture/focal length
   B. *f*-number = image distance/effective aperture
   C. *f*-number = focal length/image distance
   D. *f*-number = focal length/effective aperture
2. As the opening in the diaphragm is made smaller, the *f*-number . . .
   A. increases
   B. decreases
3. Select the number that does not represent a whole stop in the conventional *f*-number series.
   A. 64
   B. 4
   C. 1.8
   D. 5.6
   E. 1.4
4. Most lenses for 35-mm cameras are made so that they cannot be stopped down beyond *f*/22 because . . .
   A. the exposure times would be too long to hand-hold the camera
   B. it is difficult to make diaphragms with such small openings
   C. diffraction would degrade the images
   D. of reciprocity effects
5. The minimum resolving power that is considered adequate in a print to be viewed at a distance of 10 inches is approximately . . .
   A. 10 lines/mm
   B. 28 lines/mm
   C. 35 lines/mm
   D. 64 lines/mm
   E. 80 lines/mm

6. The effective *f*/number = . . .

   A. *f*-number × (image distance/focal length)
   B. *f*-number × (focal length/image distance)

7. A 50-mm focal length lens is set at *f*/8. If the image distance is 100 mm, the exposure factor is . . .

   A. 1
   B. 2
   C. 4
   D. 8
   E. 16

8. If an *f*/1.4 lens that transmits only half of the light that it would if no light were lost because of reflection and absorption is recalibrated in T-numbers, *f*/1.4 would become . . .

   A. T/1
   B. T/1.6
   C. T/1.8
   D. T/2
   E. T/2.8

9. According to the rule of thumb, the slowest shutter speed that is safe to use with a hand-held camera equipped with a 55-mm focal-length lens is approximately . . .

   A. 1/15 sec
   B. 1/30 sec
   C. 1/60 sec
   D. 1/125 sec
   E. 1/250 sec

10. When accurate between-the-lens shutters are used at high speeds with the diaphragm stopped down, the effective exposure time is . . .

    A. longer than the marked exposure time
    B. the same as the marked exposure time
    C. shorter than the marked exposure time

11. Overexposure of black-and-white film can cause . . .

    A. an increase in contrast (only)
    B. a decrease in contrast (only)
    C. either an increase or a decrease in contrast
    D. None of the above. Exposure does not affect contrast

12. If one were to test an exposure meter by exposing film in a camera, it would be best to use . . .

    A. a negative-type black-and-white film
    B. a negative-type color film
    C. a reversal-type color film

13. If a black-and-white photograph is made on panchromatic film with a red filter on the camera lens according to a behind-lens meter that has high red sensitivity, the resulting negative will probably be . . .

    A. underexposed
    B. correctly exposed
    C. overexposed

14. The term *luminance meter* is a synonym for . . .

    A. reflected-light meter
    B. incident-light meter
    C. ultraviolet radiation meter
    D. infrared radiation meter

15. When using an exposure meter with a hemispherical diffuser with a three-dimensional subject, it is recommended that the meter be aimed . . .

    A. at the main light source
    B. at the camera
    C. midway between the main light source and the camera

16. The following series of numbers (1, 2, 4, 8, 16) is identified as . . .

    A. a ratio scale
    B. an interval scale
    C. a hybrid scale

17. If a reflected-light exposure meter reading is taken from a white area in a typical scene, the resulting negative or transparency will be . . .

    A. underexposed
    B. correctly exposed
    C. overexposed

18. Using a neutral test card as an artificial midtone for an exposure meter reading with a three-dimensional subject, the card should be aimed . . .

    A. at the camera
    B. at the dominant light source
    C. midway between the camera and the dominant light source

19. With an exposure meter that has an interval scale of numbers (1-2-3-4-etc.), the calculated midtone reading for a scene in which the shadow reading is 2 and the highlight reading is 8 is . . .

    A. 3
    B. 4
    C. 5
    D. 6
    E. 7

20. An advantage behind-lens meters have over hand-held meters is . . .

    A. greater sensitivity
    B. better spectral response
    C. automatic compensation for changes in lens-film distance
    D. that they do not require batteries

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chapter

3

Strictly Digital

Photograph by Josh Shagam, Biomedical Photography Communications student, Rochester Institute of Technology

The invention of flexible roll film by George Eastman at the end of the nineteenth century had an enormous impact, not only on photography, but on our culture as well. Prior to that event, creating photographs had been the domain of professional photographers and very dedicated amateurs. That first Kodak "point and shoot" camera put photography into the hands of the masses. A hundred years later, digital imaging software has placed the darkroom on the desktops of the masses. With today's image-editing software, images can be created in a matter of hours that a master printer, several years ago, might have labored for days to accomplish.

Aliasing or a moiré pattern is an interference pattern caused by undersampling a fine regular pattern.

Table 3-1 Common Acronyms

Acronym	Definition
CCD	Charge-coupled device
CMOS	Complementary metal oxide semiconductor
DNG	Digital negative format introduced by Adobe
dpi	Dots per inch
DSC	Digital SLR camera
.jp2	JPEG 2000 file formate
.jpeg, .JPEG, or .jpg	File format (joint photographic experts group)
LCD	Liquid crystal display
LZW	A lossless file compression
ppi	Pixels per inch
RAW	File format
SLR	Single lens reflex camera
.tif, .tiff, or .TIFF	File format (tagged image file format)

Digital Camera

In many ways, a digital SLR camera (DSC) is the same as a film camera. Lenses are interchangeable, and shutters, view finders and apertures all work the same.

The differences start when a digital imaging sensor replaces the film. In most DSCs, the image sensor is smaller than a 35mm negative by one-half to one-fourth that of the 35 mm full frame, which results in a smaller angle of view. Digital technology is not restricted to the 35 mm format. Larger-format sensors referred to as *digital backs* are available for large-format cameras, although their use is still mainly by professionals because of their high cost.

The basic DSC structure consists of a lens, a shutter assembly, an image sensor, and an electronic subsystem. The electronic subsystem includes both analog and digital processing controls. The remaining elements are an LCD display, a memory card socket, and connection ports to communicate with a computer.

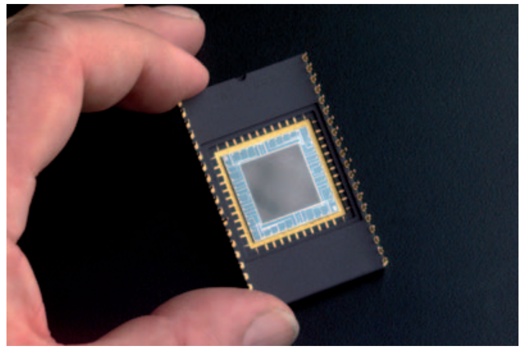

Figure 3-1 CCD sensor.

The optics used in a DSC lens are the same as those used for film cameras. However, the silicon used in the image sensor is sensitive to energy in the infrared region of the electromagnetic spectrum. Therefore, the addition of an infrared blocking filter in front of the image sensor is necessary to block energy in this part of the spectrum. Additionally, an optical low-pass filter is also placed in front of the image sensor to prevent moiré patterns or aliasing in the image.

The imaging sensor in a DSC can be a charge-coupled device (CCD), a complementary metal oxide semiconductor (CMOS) sensor, or the new Foveon X3 sensor. CCDs are the most common sensor used especially in low-end point-and-shoot cameras. See Figure 3-1. However as CMOS technology has improved, these sensors are becoming more common. Early CMOS sensors suffered from large fixed-pattern noise that negatively affected image quality and were larger than CCD arrays. CMOS sensors are growing in popularity, however, as these problems have now been corrected, coupled with the lower power needed to operate a CMOS sensor than a CCD. At the time of publication, the newest top-of-the-line DSC cameras introduced by both Canon and Nikon use CMOS sensors.

The function of the DSC electronic subsystem is to convert the analog signal that is produced by the image sensor to a digital signal. This process is often referred to as AD conversion [analog to digital (A to D) conversion]. Other processing performed by the electronic subsystem includes such things as tone adjustments, gain control, and color separations.

The digital processing in a DSC takes the digital signal and further processes the data before writing it to the magnetic media card in the camera. This can include applying a white balance correction, a color space conversion, and applying tonal corrections. In addition, the resulting image can be compressed prior to writing if required.

Digital Image Quality

Three key factors determine the quality of a digital image. They are brightness resolution or bit depth, dynamic range, and spatial resolution.

Brightness resolution is the number of discrete levels of gray quantized through the electric subsystem when the image is converted from an analog signal into digital values. This determines how many gray levels the final image will have. An 8-bit image will have 2^8 or 256 gray levels. A 10-bit image would yield 1,024 gray levels and 12 bits would produce 4,096 gray levels. In a color system, a 24-bit RGB color image has three color channels with 8 bits of data per color. Therefore, there would be 256 levels of red, 256 levels of blue, and 256 levels of green.

It has been found that in applications, such as monitor display and hardcopy output, 5 bits per color is usually enough information to represent continuous-appearing color and tones. When using a digital camera, if the output image is a jpeg file format, the cameras will sample down the number of input levels and output images at 8 bits per color, which corresponds to a luminance ratio of 256 to 1.

Dynamic range is the maximum range of light levels that an image sensor can measure or capture. More precisely, it is the ratio of the maximum measurable light intensity (just at pixel saturation) to the minimum measurable light intensity that is just about the noise level present. As ISO speed increases in a DSC, so does the noise level. The higher noise level increases the value of the minimum digital count a camera can capture, therefore dynamic range is usually decreased for higher ISO speeds.

A bit depth of 8 corresponds to a brightness resolution of 256.

Dynamic range and bit depth are both measures of the tonal quality of an image, as distinct from resolution, but dynamic range measures the difference between the lightest and darkest tones that can be captured and bit depth measures the number of intermediate tones between the lightest and darkest tones that can be rendered.

Spatial resolution is measured in pixels present in an image and is determined by the number of photocells in an image sensor. With an *area-array sensor* (an array with the photocells arranged in columns and rows), it is measured by the number of photocells or pixels in the *x* and *y* dimensions. For example, Canon's EOS-1Ds Mark III has a maximum spatial resolution of 5,616 × 3,744 pixels.

The spatial resolution of a *linear-array* sensor (an array with just one row of photocells) is determined by the number of photocells in the line and the number of measurements made in the scanning direction. Most scanners or cameras that use a linear array sensor move it across the imaging area with a stepper motor. At each step, the output of the array is read out and sent through

An 8-bit image will have 2^8 or 256 gray levels.

Dots per inch (dpi) is a measure of the printing resolution of a printer and describes the number of ink or toner drops in a linear inch.

Pixels per inch (ppi) is a measure of the resolution of a display, a scanner, or a digital camera

For near-photo image quality, a camera resolution of about 150 to 200 pixels per inch of the display print is needed. A 4 × 6-inch print would require a resolution of at least 600 to 900 pixels.

A megapixel is 1,000,000 pixels.

the electronic subsystem. The spatial resolution in the direction that the sensor is moved is equal to the number of steps that it takes to move across the image. If the sensor is 2,048 pixels wide and is moved 3,000 steps, and a sample is taken at each step, the resolution of the resulting image would be 2,048 × 3,000 pixels. One method of increasing spatial resolution with a given size of linear-array sensor is to reduce the step size to half a pixel width and to repeat the scan with the sensor shifted laterally half a pixel width. Another method is to electronically interpolate the data between pixel positions.

The resolution of slide and print scanners is expressed as *pixels per inch (ppi)* since the size of the scanning area is known. A 35 mm film scanner scans an area roughly 1 × 1.5 inch, and most consumer flatbed print scanners are designed to measure an area as small as a credit card up to legal document size of 12 × 17 inches. Many scanner manufacturers refer somewhat imprecisely to the resolution of their scanners in *dpi* (dots per inch), which should be reserved for describing certain types of *output* devices.

Many manufacturers will also state an "effective" resolution, which is a clue that they are not describing the actual optical resolution. Effective resolution usually means the resolution after *interpolation* (creating new pixels by averaging between sampled ones) to achieve a higher resolution.

The resolution of digital cameras is best expressed as the number of horizontal and vertical pixel measurements made by the sensor, such as 5,632 × 3,750. Many camera manufacturers advertise the total number of pixels (horizontal pixels multiplied by vertical pixels), which for the example here would be 211,200,000, which is shortened to 21.1 megapixels.

Artifacts

Artifacts are unwanted defects in a digital image. One common cause of artifacts is the result of *insufficient spatial resolution* to capture a particular type of scene. A scene with high-frequency information (rapid variations in intensity), such as a white picket fence may show gaps or variations in the width of the individual pickets if too few samples are taken to capture the information. The first generation of consumer digital cameras typically had sensors with resolutions of about 640 pixels by 480 pixels. Outdoor scenes taken with these early cameras often reproduced high-frequency areas, such as grass, as just square patches of green shades because there weren't enough pixels to capture details as small as individual blades of grass. Or, as illustrated in Figure 3-2, the hair is not distinguishable in the low and medium sample rate images.

Aliasing, also referred to as stair stepping, is another form of artifact typically seen as jagged edges on diagonal lines. This type of artifact is seen especially along the arm in Figure 3-2 in the low and medium sample rate images. Most pixel-level artifacts become much less objectionable with higher sampling rates because the individual pixels are much smaller.

Pixel defects are another unavoidable type of artifact with digital sensors. Making a sensor that is totally free of defects is nearly impossible because of the large number of pixels. There are *hot* pixel defects, in which the pixel has a high dark-current noise, and there are *dark* pixel defects, in which the pixel has a lower response than surrounding pixels. *Column* defects are usually caused by pixels that interfere with the charge transfer process causing all or part of a column of pixels to appear dark.

Figure 3-2 Sampling resolution: low (left), medium (middle), and high (right).

Noise

The level of *noise* produced by the sensor also determines the final quality of a digital image. Noise appears as random variations in the brightness levels or colors and is usually more prevalent in the shadow areas of a scene. Noise is caused by a number of different factors. A sensor will generate some current even when not exposed to light. The electrons within the photocells can be excited to move by heat alone. *Dark current*, as this type of noise is called, is the result of surface states within the chip and is a function of temperature and time. Long exposures and high operating temperatures will increase the level of noise in the output signal.

For scientific applications such as astrophotography, a variety of cooling techniques are used to lower the sensor temperature to around -50°C, which reduces the dark-current noise. This also allows for integration times as long as 30 minutes. Cooling of this type obviously isn't practical for most digital camera applications. Exposures of longer than 1/3 of a second are generally not recommended for digital cameras because of the noise levels generated during exposures over that period of time. Other causes of noise include readout noise (created by the output preamplifier) and cosmic noise (caused by cosmic radiation), which increases with longer exposure times.

The nominal ISO rating of a digital camera is set by most manufacturers such that the black level is just above the point where noise becomes objectionable. Many manufacturers will offer several higher ISO settings from nominal as an option. A higher ISO rating allows an image to still be captured even though those images will generally have higher levels of noise. *Signal-to-noise ratio* is a measure of how much noise is present relative to the signal strength (see Figure 3-3).

The higher the signal-to-noise ratio, the better the image.

File Formats

Many different file format options are available in which to save digital images. DSCs will offer several format options. These almost always include a native RAW format and several JPEG options. Additionally some will offer TIFF as an option. When the image is moved to a computer, many more options are then available.

There are two basic approaches to saving digital data. The first is a

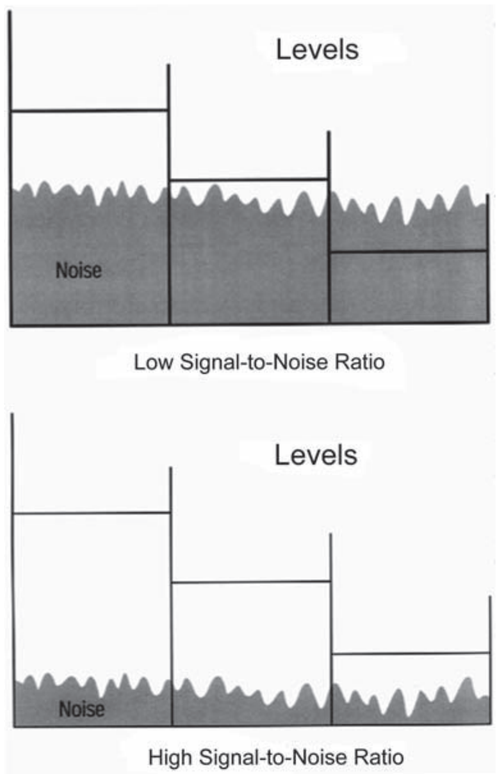

Figure 3-3 Signal-to-noise. The signal strengths, indicated by the heights of the three horizontal lines, are the same in both examples but the higher (gray) noise level in the top situation is stronger than the weakest signal and almost as strong as the second strongest signal.

lossless file format. This is one that preserves all the original data, so that when the file is opened at a later time, all the original digital counts are preserved. The second option is a lossy file compression format. This approach removes redundant data from the file to reduce the final file size, thus saving disk space. This can cause image quality loss, especially in areas of fine detail. Using a lossy file compression destroys the original data that were recorded by the camera. They can never be recovered.

RAW image files contain data from the image sensor that have minimal if any processing done to them. RAW file formats often save the data prior to interpolating to full RGB data. A RAW file is sometimes referred to as a *digital negative*. This is because, in principle, they are similar to a film negative. This should not be confused with the DNG file format, which is also referred to as digital negative. A film negative is used to create the final print, just as a RAW file is. In the darkroom printing process, a photographer can manipulate the final print made from the film negative using techniques such as dodging or burning or adjusting the contrast by selecting a particular grade of printing paper. A photographer can achieve all these same effects using image editing software and the RAW file.

RAW files have to be processed by a converter before they can be used. This is considered a drawback by some, as there is no standard RAW format. Manufacturers have their own individual proprietary formats. As improvements are made to the formats, older versions may become obsolete, making older files unaccessible to new software.

Adobe introduced the DNG (digital negative) file format in 2004. It is a royalty-free RAW image format and was developed in response to the demand from users for a common format. The DNG file format is gaining popularity and is supported by Hasselblad, Leica, Pentax, Ricoh, Samsung, Apple, and Sea & Sea. The OpenRAW file format introduced by the OpenRAW working group in 2006 is another attempt to unite all companies to use a common RAW format. Although both formats have some support from industry, many of the big camera manufacturers are continuing to use their own proprietary formats.

JPEG (Joint Photographic Experts Group) is a common compression format used in photography. JPEG is a standard format and is recognized by all image-editing software packages. There are two JPEG formats, the original

JPEG format which has a file extension of .jpeg or .jpg. This format is widely used. The second is JPEG 2000, file extention .jp2. JPEG 2000, provides options for both lossy and lossless compression of image data. When selecting the lossy compression option, the degree of compression or, in other words, the resulting quality of the output image can be selected by the user. This format is not as widely used yet.

A TIFF (tagged image file format) is a file format that is used for both line art and photographs. Just as with JPEG, TIFF is widely supported by most image editing software. TIFF is a lossless file format, but has the option to use a LZW compression. LZW is a lossless compression technique created by Abraham Lempel, Jacob Ziv, and Terry Welch in 1984.

Digital Image Processing

The first step in the digital-imaging chain is getting an image onto a computer, whether by scanning existing images, by photographing a scene with a digital camera, or by creating an image using software. Once in a digital format the image is now just a series of numbers that can be mathematically manipulated any number of ways. If the result isn't what you wanted, click on "Undo" and start over!

Every trick of the master printer's trade and some they never imagined can be accomplished with existing image-processing software. Adjusting *tonal range*, *tonal placement*, *tonal contrast*, *color balance*, *color saturation*, and *sharpness* are all easily accomplished with a few clicks of a mouse. Complex masks can be easily created, allowing these same adjustments to be made to just the selected portions of the image. Image defects such as dust and scratches can be easily removed with a technique called *cloning*. The cloning brush copies information from an adjacent area to replace the defect by effectively blending similar tones and textures over the defect. No more spotting and retouching prints! Retouch the image once digitally, and every print thereafter is free of those defects. Some image-editing programs now even offer automatic algorithms that search out defects such as dust, scratches, and red-eye, and attempt to fix these problems with little user intervention.

Image-editing programs use a variety of mathematical functions to perform different processes on an image such as analysis, pixel point processing, pixel group processing, frame processing, and compression.

Note: For the purpose of illustrating the following concepts of image processing, various tools and dialog boxes from Adobe's PhotoShop software were used, but many other packages provide very similar tools.

Histograms

Analysis of digital data can now start at the time of exposure. Digital cameras now can show the photographer a histogram of the digital data as soon as the image has been captured, allowing a photographer to determine if the exposure was correct. If not, the photographer can make an adjustment to the exposure and reshoot the image instantly.

A histogram shows the distribution of digital values for all of the pixels in the image area (see Figure 3-4). The bottom axis represents the entire grayscale from 0 to 255. The vertical lines represent the number of pixels or frequency of each value in the image. If the image is an RGB color image, a histogram can be viewed for each of the individual color channels as well.

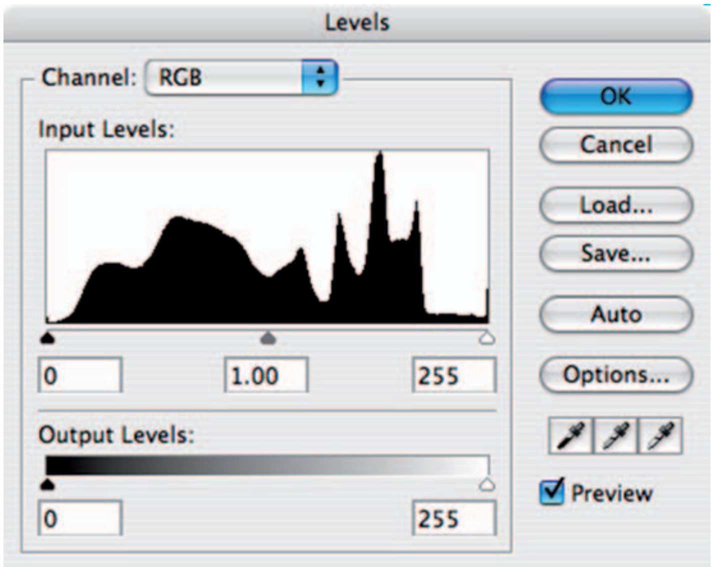

Figure 3-4 Full-image histogram.

Viewing an image histogram provides a visual representation of the type of image that you have. A high-key image would have many of the pixels at the higher digital values to the right of the histogram, which is where highlight detail is. A low-key image would have many pixels at the left end of the histogram where the shadow detail is. An image with good dynamic range will have a histogram with values extending most of the way from 0 to 255. Having a large number of pixels at 0 or 255 would indicate that the image was either under- or overexposed.

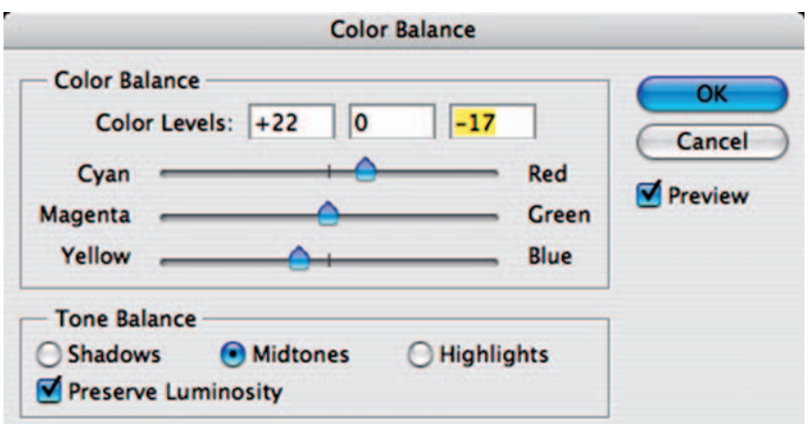

Figure 3-5 Color-balance tool. Color balance can be selectively adjusted for shadows, midtones, or highlights.

Pixel Point Image Processing

Pixel point processing is the most basic image-processing operation and can be used to correct images with contrast or color balance problems. Pixel point processing uses a mathematical function to map the original pixel values to new output values, lightening, darkening, or changing the contrast of an image. The simplest form of image remapping is called *slide mapping*. Adding or subtracting a constant value to all pixels in the image will alter the overall *brightness*. This has the effect of moving all the values in the histogram to the right or to the left, basically what a brightness control for a video screen does. The drawback to slide mapping is that if you add 50 to all pixel values, then all the pixels whose values were above 205 or higher will become 255 and highlight detail will be lost. Conversely, if you subtract 50 from all pixel values, then all pixels whose values were 50 or below will become 0 and shadow detail will be lost. Slide mapping should be used carefully because it is easy to permanently lose image data.

A constant value applied to only one of the color channels will change the overall color balance of the scene. The *color-balance tool* uses this technique. PhotoShop's color-balance tool also allows one to weight the value, applying it more toward the shadows, midtones, or highlights (see Figure 3-5).

The next type of mapping is *stretch mapping*. Stretch mapping uses multiplication or division by a constant to stretch or contract the tonal values over the histogram, which can be used to stretch a low-contrast image over the full range of values to produce normal contrast. The *Levels tool* does

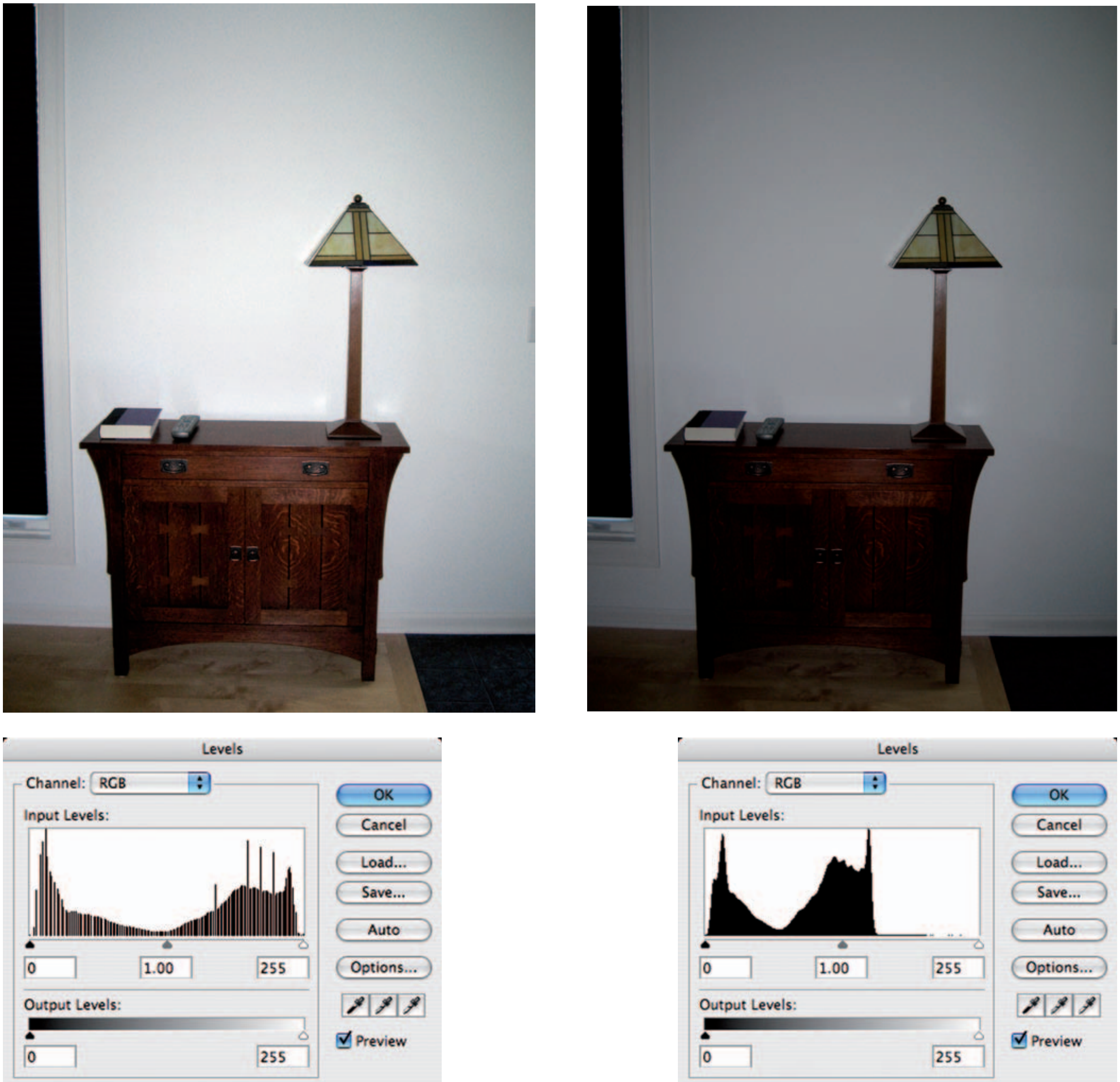

Figure 3-6 The Levels tool is used to apply stretch mapping, which controls image contrast.

the math automatically. By moving the black point and white point control triangles under the histogram, you can stretch the values out over the range of 0 to 255 (see Figure 3-6). *Complement mapping* inverts all the values in the image: black becomes white, white becomes black, and gray values are mapped to their complementary tones above and below a middle gray.

The middle-gray triangle in the Levels tool is used to adjust gamma. It affects the midtones, while not changing the white or black point. Instead of applying a constant value, the midtones are changed using a Gaussian (normal) distribution, with greater amounts of change in the middle values and decreasing amounts toward the highlights and the shadows.

The Levels tool corresponds to different contrast grades of photographic paper.

Local image contrast can be adjusted with the Curves tool.

Moving the middle-gray triangle to the left lightens midtones, and moving it to the right darkens midtones.

The *Curves tool* allows remapping of an image based on a drawn curve by changing the curve shape. A straight diagonal line results in no change, but by drawing an S-shaped curve the shadows can be darkened and the highlights lightened with less change to the midtones. This tool allows very fine control over gray-level distribution that is simply not achievable with the Levels tool. Clicking on an area in the image highlights that value on the curve.

Pixel Group Image Processing

In *pixel group processing*, used to create a variety of special effects, a mathematical function called a *convolution* uses the values of the surrounding pixels to determine a new value for each pixel (see Figure 3-7). As the matrix or kernel slides over each pixel in the image, the values of pixels falling within the matrix are multiplied by the factor in each cell of the matrix. The sums of that process are added together to create a new value for the center pixel. These new values are stored, creating a new image,

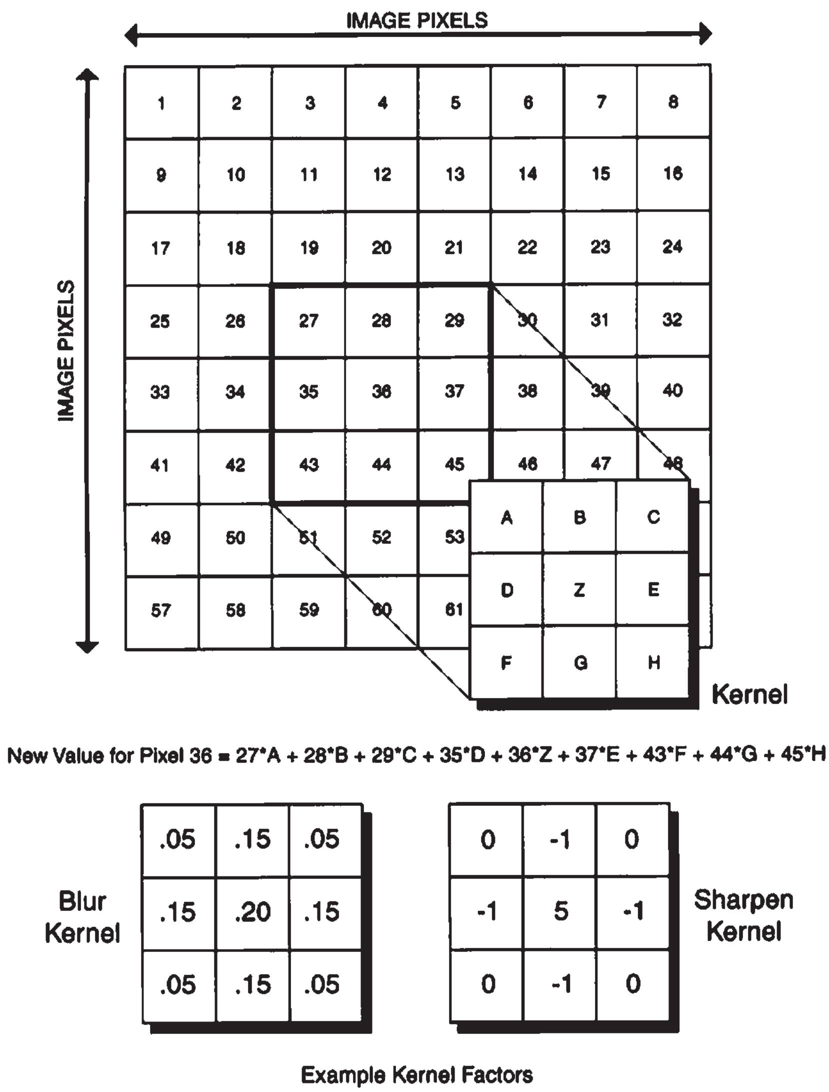

Figure 3-7 Convolution filters use for a variety of special effects, including blurring and sharpening the image.

so that previously processed pixels don't affect the current pixel. The sum of the factors in the matrix should equal 1 to maintain the same brightness levels in the new image.

Blur and *sharpening filters* are two common examples of convolution filters. Several other filters that use this technique are the *median filter*, which is useful in reducing noise or halftone screen patterns in an image, and the *emboss filter*, which creates the effect of a bas-relief image with shadows and highlights along edges in the image.

Probably the most used filter in digital imaging is the *unsharp mask filter*. The unsharp mask filter is a sharpening filter. Whether using a digital system or a film-based system a blurry image cannot be made unblurry, however it can be sharpened. A sharpening filter provides an apparent increase in edge sharpness by increasing the contrast along edges. It is interesting to note that human eyes have a similar capability, by altering the sensitivities of the rod and cone sensors on opposite sides of image edges.

The unsharp mask filter is quite flexible, having three parameters that can be adjusted to meet the needs of any particular image. The three parameters are *amount*, *radius*, and *threshold*. The unsharp mask is not an edge detector; instead it locates pixels within an image that differ by a threshold value you have set. Once it locates pixels that exceed the threshold value, the lighter pixel is lightened and the darker pixel is darkened by the amount value set. The final value, radius, tells the software how to set the region to which each pixel is compared. Increasing this value increase the edge effects.

Caution must be exercised when using any sharpening filter. Oversharpening an image can produce halos around edges. See Figure 3-8.

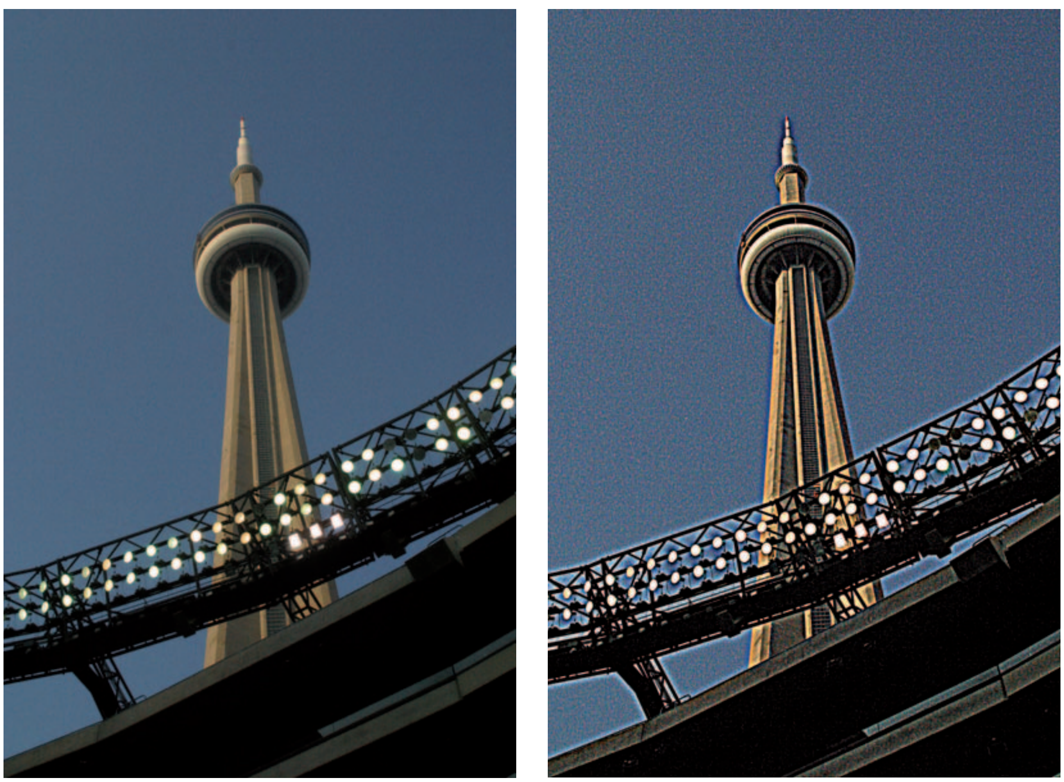

Figure 3-8 The image on the right has been over-sharpened, creating a halo around objects and increasing the visibility of the noise.

Bicubic interpolation will produce the highest quality image when downsizing or upsizing an image.

Additionally, sharpening can also cause noise to become more apparent in an image, which can be easily seen in areas with little detail such as the sky. One common method to avoid this when sharpening color images is to only sharpen the red and the green data. The blue data are then either left alone or actually smoothed. The blue data will have the most noise present because of the lower sensitivity of silicon to blue wavelengths.

Frame Image Processing

Frame image processing is applying a function, such as rotation, scaling, and color-space transforms, to a region or the whole image. Rotations such as 90 or 180 degrees simply reorder the columns and rows of pixels in an image.

Scaling or *resizing* an image is another form of frame processing. There are many methods for performing tasks. When reducing the size of an image, the simplest method uses a technique called *decimation*. Decimation means not using all of the available pixels. If an image is reduced by 50%, half the pixels in each direction will be discarded, leaving just one-quarter the number of pixels. This method does not produce very good results.

The simplest method for increasing the size of an image is *pixel replication*, often referred to as "nearest neighbor." In this method, if the image needs to be doubled in size, replication will take each pixel and duplicate it to create the new image. This method will cause the image to become increasingly more pixilated-looking because, in effect, it just enlarges each pixel. Edges will often be jagged in the resulting image

Interpolation is the preferred approach for both downsizing and upsizing images. This technique creates new pixels by calculating a new value based on the surrounding pixels. There are two algorithms used for interpolation: *bilinear* and *bicubic*. Bilinear is a medium-quality interpolation algorithm and uses four neighboring pixels to calculate the new pixel values. Bicubic is a very high-quality interpolation algorithm that uses 16 surrounding pixels in its calculations but as a result takes much longer to process.

Digital Printing

The choices available for creating photographic-quality digital-color output are constantly growing. The options range from inexpensive desktop ink-jet printers to room-size printers that utilize lasers to write directly onto photographic paper (and cost several hundreds of thousands of dollars). All digital printers do have one thing in common: a print engine that writes dots onto paper or some form of receiver material.

Continuous-Tone and Halftone Output

How the dots are created allows us to categorize printer output into one of two distinct categories, *continuous tone* or *halftone*. Continuous-tone digital printers produce output that is strikingly similar to the traditional color photographic process. Many digital printers are even printing on conventional color photographic materials.

Continuous-tone printers write individual image pixels directly to paper or film. The dots created are of varying density (usually 256 levels or 8 bits per color) and the dyes used are transparent. This allows one color to be placed directly on top of the previous color. The dyes combine to create

a very wide range of colors. A printer using the three primary colors of cyan, magenta, and yellow (most continuous-tone printers don't use a black dye but instead create a process black by combining equal amounts of cyan, magenta, and yellow) is theoretically capable of reproducing more than 16.7 million colors. The color gamut of the dyes used will determine the actual number of colors that can be reproduced.

Halftone output is similar to that created by the large printing presses used in magazine and newspaper reproduction. Halftone printers create dots that are opaque and do not vary in density. Halftone dots, therefore, can't be placed on top of one another without obscuring the previous color. Each image pixel must be converted into a pattern of varying amounts of cyan, magenta, yellow, and black dots. These patterns of small dots blend in the eye and are perceived as various colors when viewed from a distance. This process is called *halftone screening*.

The computer brought radical changes to the halftone-screening process. The traditional method for screening a photographic image was to copy the photograph using a large-process camera. An exposure was made through a contact screen onto high-contrast sheet film, one exposure for each color. The contact screen was a sheet of film with a precisely exposed crisscross pattern of varying densities. A different screen was used for each color and had the crisscross pattern rotated at various angles, black at 45 degrees, magenta at 75 degrees, yellow at 90 degrees, and cyan at 105 degrees. These screens would break the image up into a series of dots of varying frequencies and sizes corresponding to the amount of that particular color in the image to be printed. The resulting high-contrast films would be used to expose the printing plates. The screens were angled to prevent moiré patterns in the final image and resulted in the familiar rosette pattern of the halftone screen.

With the advent of the computer, the whole photomechanical screening process was eliminated. The computer could mathematically convert an image into screened dots and even write it directly onto the high-contrast films using printers such as the Linotype laser typesetter. Today, computers can even write directly to the printing plates themselves with units such as Heidelberg's digital direct-to-plate presses. New ways of screening images also became possible: *stochastic* or *error-diffusion* screening, for example, in which the dots are generated in random patterns that increase or decrease in frequency depending on the color and density of the image. This would have been extremely difficult to accomplish without the use of a computer. This technique is now widely employed by many inkjet printers and it significantly boosts the apparent resolution of a printer.

A printer having about 600 dpi can produce near-photo-quality prints.

Continuous-Tone Printers

Printer resolution in dpi (dots per inch) does not correspond to pixel resolution. It is how close the printer can place ink droplets on paper.

The following are examples of some different types of *continuous-tone printers*. This is hardly a complete list but attempts to illustrate just some of the technologies available.

Film Recorders

The first devices adapted to computer output were those originally designed

as hard-copy printers for analog video or television. In the mid-1980s manufacturers such as Polaroid, Beseler, and Dunn Instruments introduced film recorders that would allow print or film materials to be exposed by sending a video signal to a specially designed flat monochrome cathode-ray tube (CRT). A camera (often a standard 35-mm back with a flat-field lens) was pointed at this CRT within a light-tight housing, the shutter was opened, and the image was drawn line by line on the face of the CRT. To create a color image, a color filter wheel with red, green, and blue filters was utilized. The image would be drawn three times, once each for red, green, and blue color channels.

The second generation of film recorders were specifically designed for computer use and featured higher resolutions (2,000 lines or more) and digital interfaces. Instead of analog video, digital image files from digital scanners could now be processed using software to enhance the image and then output to film directly from the computer. It could then be printed conventionally. This was the only high-quality solution for several years.

Film recorders are still in wide use today, mostly in applications that require extremely high resolution and where turnaround time is not an issue. Some of today's high-end film recorders, such as the Symbolics and Management Graphics models, have resolutions of up to 16,000 lines and can output on film sizes from 35-mm to 8 × 10-inch sheet film.

Recently, devices that print directly to photographic paper have been making rapid in-roads into professional labs. This is largely due to their ability to print digital images directly to large paper sizes. Several different technologies are being used in these printers and are listed below.

Light-Emitting Diode (LED)

The LED printer, such as Kodak's Pegasus LED printer, prints directly onto special digital photographic paper using a small array of LEDs. The Pegasus printer is a roll-fed printer that can handle roll sizes up to 20 inches wide. The paper is fed into a drum where a vacuum pump pulls the paper tight against the inside of the drum. The drum will accommodate a 33-inch-long piece of paper, allowing a maximum 33 × 20-inch image to be printed.

The image is exposed by a small array consisting of four red, four green, and four blue LEDs mounted at the end of a counterbalanced arm. The arm spins on a spiral track at about 1,350 RPM. The LED lens assembly spins just above the paper's surface, writing the image as the arm travels down the length of the drum on the spiral track. After the image is written, the paper is advanced into an attached processor for development, and exits dry in about 6 minutes. LVT is another company manufacturing printers that utilize LED diodes for exposing photographic film and paper. Instead of the paper being drawn by a vacuum to the inside of a drum, the paper is wrapped around the outside of a drum. The output of the red, green, and blue diodes is combined to create a single spot that is then focused to write the image.

Laser Diode (Laser)

The Durst Lambda printer is one of the more popular digital printers on the market. Utilizing a series of laser diodes to write a digital image directly onto photographic paper, the Lambda printer can handle rolls of paper up to 50 inches wide, and it writes to the paper as it moves past the laser imager. As a result, much larger images can be

written than the limits imposed by the circumference of a drum as with the LED printers.

Thermal Transfer

Another technology that started out as a video output device was thermal *dye-diffusion* printing. In the mid-1980s both Sony and Kodak introduced printers that produced a continuous-tone image from a video source using the thermal dye-diffusion process.

The thermal dye-diffusion process uses a two-part medium. The first part is a clear Mylar film material, called a donor ribbon, onto which consecutive transparent cyan, magenta, and yellow dye patches are coated using a process similar to gravure. The second part is a specially coated paper-based material called the receiver. The donor material resides on a spool driven by a motor. A thermal print head containing thousands of individually controllable resistive elements is used to heat the dyes on the donor material and thereby transfer the dye from the donor material to the receiver. The amount of dye transferred is controlled by varying the amount of current (and thus heat) sent to each of the resistive elements on the print head. Stepper motors drive the receiver paper and the donor material past the resistive head. One color patch is printed at a time and the paper is rewound back to precisely the same starting point each time so that the next color is placed in registration with the preceding one.

It is important to note that the dyes are transparent and that the density can be varied up to 255 different levels for each color. Because the dyes are transparent, the color dots are placed on top of one another, combining to create any of the 16.7 million theoretically possible colors in a 24-bit image.

Halftone Printing Technologies

Thermal Wax Transfer. A similar technology, known as thermal wax transfer, appeared around the same time as dye diffusion. Opaque wax colorants are coated in patches onto a ribbon like those used in dye diffusion. The thermal head melts the wax and transfers it to the paper. One advantage of thermal wax was that it did not require a special receiver material; plain paper could be used. The quality of the images produced was limited by the fact that it was a fairly low-resolution (300 dpi) halftone device. As a result, it was generally used as an output device for business graphics or proofing.

Phase-Change. Actually considered a form of inkjet, phase-change technology has similarities to the thermal wax printer. Instead of wax-based dyes coated on a thin transport ribbon, phase-change devices use a solid wax that is melted and then sprayed via nozzles onto the paper—hence their nickname "crayon spitters." Tektronix is the major manufacturer of both wax-transfer and phase-change technology printers.

Electrophotographic. This technology initially developed for copiers found its way into desktop printers with the introduction of the laser printer in 1985. A laser, directed via a spinning mirror, is used to alter the magnetic charge on a rotary drum. Toner particles are then attracted to these areas of the drum, and as the drum rotates into contact with the paper the toner particles are transferred to the paper. The paper is transported through a pair of heated rollers, fusing the toner particles to the paper. The color process adds cyan, magenta, and yellow toners to the process and

Gravure, from the French word *graver* meaning to engrave. It is a process for quality printing using etched plates or cylinders.

The Image Permanence Institute researches preservation of recorded information, including photographs. Their website is http://www.imagepermanenceinstitute.org/.

requires exposing the electrostatic drum once for each color.

Prints made with fused toner are relatively inexpensive per sheet compared to most other technologies discussed here. However, they do not hold up well over time.

Inkjet Printers. Inkjet technology is one of the more rapidly changing technologies because of the enormous amount of development dollars being spent on it. The primary reason is because it is one of the few technologies affordable enough for the home consumer.

Thermal or Bubble Jet. The most common inkjet technology is the thermal or bubble-jet system found in printers made by companies such as Canon and Hewlett-Packard. This technology is referred to as drop-on-demand (DOD). Each ink cartridge contains a series of tiny nozzles and an electrical connection to the printer. The ink is routed into a series of individual chambers, each with a tiny resistive heating element. A pulsed current applied to the heating element heats the ink until it vaporizes, causing a bubble to form. The expanding bubble forces the ink through the small opening in the chamber and sprays it toward the paper. The vacuum created in the chamber draws more ink into the nozzle.

The cost of replacement cartridges as a result is relatively high with this type of technology. When the ink cartridges are replaced, the head technology is replaced as well, even though it may still have much useful life left.

Ink stability has been a major problem with most desktop inkjet printers. Most inkjet prints have a display life measured in months or, at best, a few years. New waterproof inks and pigmented inks are beginning to become available for the larger-format printers, and are trickling down to the desktop printers as well.

Piezoelectric. Piezoelectric inkjet printers, instead of using a heating element to force the ink out of the nozzle, use a small piezoelectric crystal that expands when a current is applied. The piezoelectric jet is like a small electromechanical pump and can deliver a very small amount of ink very precisely. Used by Epson in their line of desktop printers, piezoelectric technology is currently capable of resolutions up to 1,440 dpi. The drawback to this technology has been printing speed, but advances are being made with each new generation of printer.

The inks available from Epson fare little better than those of most desktop inkjet printers. In response to the popularity of the Epson printers (because of their photo-quality output), a number of third parties have begun providing alternative inks, cartridges, and papers that promise archival-quality prints.

Continuous-flow. Continuous-flow or "hertz" inkjet printers pump a continuous stream of electrically charged ink droplets (more than 4 million per second) at the paper. A magnetic field is used to control ink placement on the page; unused ink is directed to a recovery reservoir.

Continuous-flow inkjet printers are available for several distinctly different types of applications. The high-speed, low-resolution variety are used in applications such as product identification, personalized direct mail, and addressing catalogs and magazines.

The high-resolution, low-speed printers, such as the IRIS series by Scitex, are used for proofing and fine art printing. IRIS printers can produce multiple spots per dot and can achieve effective resolutions of up to

1,800 dpi. In part because of the great number of paper surfaces that it can print on (especially heavier weight, fine art water-color papers), the IRIS has become one of the most popular printers for fine-art reproduction. These prints are often referred to as Giclée (pronounced ghee-clay), which is really just a fancy French name for inkjet. Giclée prints made using the latest archival inks have been tested to have a display life of up to 75 years and perhaps even longer.

Archival Considerations

New inks and receiver materials are coming to market every day. To keep up with any of these new technologies, there are newsgroups and forums available via the Internet where the latest information can be shared and discussed with others. One Web site that will prove invaluable is that maintained by Henry Wilhelm of Wilhelm Imaging Research Inc. at http://www.wilhelm-research.com.

Henry Wilhelm is considered the leading expert on print permanence and is constantly testing the display life of new photographic papers, inks, and inkjet papers. The Web site is frequently updated to reflect the latest testing results.

REVIEW QUESTIONS

1. The light recording technologies used by most digital cameras and scanners is . . .
   A. ADC
   B. CAD
   C. CCD
   D. EPS
2. The yield of a 10-bit ADC in terms of gray values is . . .
   A. 4,096
   B. 1,024
   C. 256
   D. 128
3. The advantage of having a sensor with twelve or more bits is similar to films with . . .
   A. higher ISO speeds
   B. greater exposure latitude
   C. less graininess
   D. increased sharpness
4. Aliasing is most pronounced in an image with edges that are . . .
   A. horizontal
   B. vertical
   C. diagonal
5. Most commercially available silicon CCDs are . . .
   A. frontside-illuminated
   B. backside-illuminated
   C. topside-illuminated
   D. splitside-illuminated
6. The most common type of area array CCD is . . .
   A. progressive scan
   B. frame transfer
   C. pixel-scan transfer
   D. interline transfer
7. One disadvantage of a frontside-illuminated CCD is its poor spectral response in the . . .
   A. blue region
   B. blue-green region
   C. blue-red region
   D. green-red region
8. High-end drum scanners typically use . . .
   A. CCD sensors
   B. vertical pixel arrays
   C. photomultiplier tubes
   D. horizontal pixel arrays
9. The simplest form of image remapping is called . . .
   A. stretch mapping
   B. complement mapping
   C. slide mapping
   D. pixel point mapping
10. The most affordable type of printer for home consumer use is . . .
    A. bubble jet
    B. electrophotographic
    C. thermal wax transfer
    D. inkjet
    E. laser

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chapter

4 Photographic Optics

Photograph by Professor Michael Peres, Biomedical Photographic Communications, Rochester Institute of Technology

Image Formation with a Pinhole

The *pinhole*, as an image-forming device, has played an important role in the evolution of the modern camera. The observation of images formed by a small opening in an otherwise darkened room goes back at least to Aristotle's time, about 350 B.C.—and, indeed, the pinhole camera still fascinates many of today's photography students because of the simplicity with which it forms an image. The darkened room, or camera obscura, evolved into a portable room that could be moved about and yet was large enough to accommodate a person. The portable room in turn shrank to a portable box with a small opening and tracing paper, used as a drawing aid. By about 1570, the pinhole was replaced by a simple lens that produced a brighter image that was easier to trace. The name camera obscura survived all these changes.

Going back to the discussion of light in Chapter 1 and the corpuscular theory of light, pinholes are able to form images because light travels in a straight line. For each point on an object, a reflected ray of light passing through the pinhole will fall on only one spot on the ground glass, film, or digital sensor. Because light rays from the top and bottom of the scene and from the two sides cross at the pinhole, the image is reversed vertically and horizontally so that lettering in a scene will appear correct on the ground glass if it is viewed upside down (see Figure 4-1) and on film images viewed through the base.

A pinhole aperture on a view camera operates somewhat like a zoom lens.

The pinhole camera is still celebrated yearly with Worldwide Pinhole Photography Day http://www.pinholeday.org/

Image definition varies with the size of the pinhole aperture, and there is an optimum size for a given pinhole-to-film distance.

A pinhole camera has two components—the pinhole-to-film or image distance, and the diameter of the pinhole itself. If a pinhole is used on a view camera or other camera having a bellows, it is the equivalent of a zoom lens because the image size will increase in direct proportion to the pinhole-to-film distance. The angle of view, on the other hand, will decrease as the image distance increases (see Figure 4-2). Because a pinhole does not focus light as a lens does, changing the image distance has little effect on the sharpness of the image. However, when the image is examined critically, it is found that there is an optimum pinhole-to-film distance for a pinhole of a given diameter.

Increasing the size of a pinhole from the optimum size allows more light to pass, which will increase the illuminance at the film plane and reduce the exposure time, but it also reduces the image sharpness. Decreasing the pinhole size, however, does not increase image sharpness. When the size is decreased below the optimum size for the specified pinhole-to-film distance, diffraction causes a decrease in sharpness (see Figure 4-3). The optimum

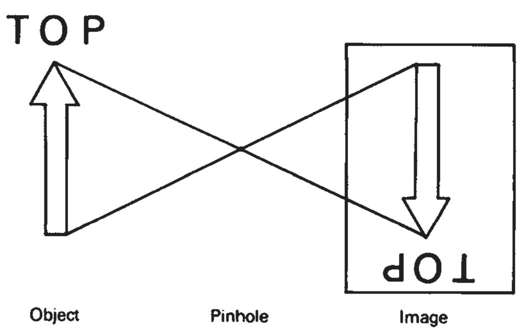


Figure 4-1 Reversal of the image vertically and horizontally by the crossing of the light rays at the pinhole produces correct reading of the lettering if viewed upside down from the rear.

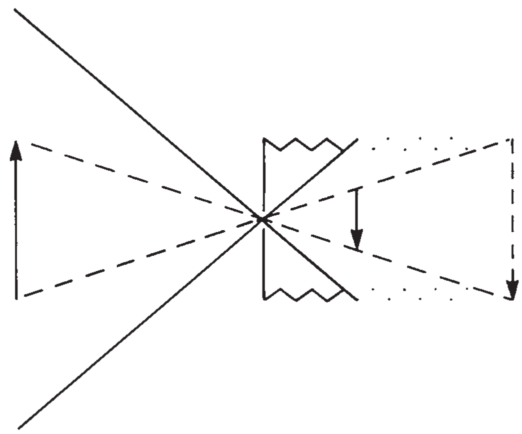
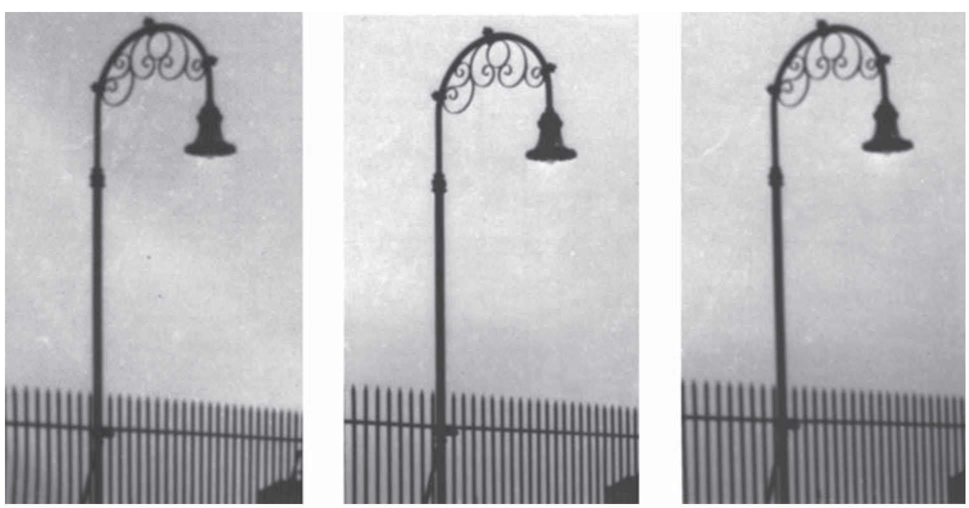


Figure 4-2 As the pinhole-to-film distance increases, the image size increases and the angle of view decreases.



A B C

Figure 4-3 Three photographs made with pinholes of different sizes one-half the optimum size (A), the optimum size (B), and two times the optimum size (C). The images represent small sections cropped from 8 × 10-inch photographs.

pinhole size (Eq. 4-1) can be calculated with the formula

$$D = \frac{\sqrt{f}}{141} \qquad \text{(Eq. 4-1)}$$

where D is the diameter of the pinhole in inches, and f is the pinhole-to-film distance in inches (see Table 4-1).* For example, with a pinhole-to-film distance of 8 inches, the diameter of the optimum size pinhole is about 1/50 inch. A No. 10 needle (a very fine sewing needle) will produce a pinhole of approximately this size.

If millimeters are used as the unit of measurement, the following formula (Eq. 4-2) should be used:

$$D = \frac{\sqrt{f}}{28} \qquad \text{(Eq. 4-2)}$$

There is a basic pinhole formula that takes into account the wavelength of the light, $D = \sqrt{2.5\lambda f}$, where λ is the average wavelength of the exposing radiation in millimeters. For white-light and panchromatic film, a value of 500 nm (.00050 mm) is used. The optimum pinhole size is somewhat smaller for photographs made with ultraviolet radiation and somewhat larger for photographs made with infrared radiation. Doubling the wavelength or the pinhole-to-film distance will increase the size of the optimum pinhole by a factor of the square root of 2 or 1.4. Various references do not agree on the constant in the formula, and the 2.5 constant used above represents an average value.

Pinholes can be made by pushing a needle through a piece of thin, opaque material, such as black paper, or drilling a hole in very thin metal. It is also possible to make a pinhole by crossing a vertical slit in one piece of thin material with a horizontal slit in another. The fact that this pinhole is square rather than round is of no great importance. Placing the vertical and horizontal slits at different distances from the film produces different scales of reproduction for the vertical and horizontal dimensions of objects being photographed, that is, an anamorphic image. Because the vertical slit controls the horizontal image formation, placing the vertical slit at double the distance of the horizontal slit from the film will produce a horizontally elongated or stretched image with a 2:1 ratio of the two dimensions (see Figure 4-4).

Note that throughout the discussion of pinhole cameras, it was assumed that film was the light-sensitive material. Pinhole images can be created by replacing the lens on a digital camera with a pinhole.

Anamorphic images can be produced with a pinhole formed by vertical and horizontal slits at different distances from the film.

Table 4-1 Optimum pinhole diameters for different pinhole–film distances

f (Distance)	D (Diameter)	*F*-N (*F*-Number)
1 in.	1/140 in.	*f*/140
2 in.	1/100 in.	*f*/200
4 in.	1/70 in.	*f*/280
8 in.	1/50 in.	*f*/400
16 in.	1/35 in.	*f*/560

$D = \sqrt{f}/141$ (in.) Optimal pinhole size equation for focal length in inches

$D = \sqrt{f}/28$ (mm.) Optimal pinhole size equation for focal length in millimeters

$F - \mathrm{N} = f/D$

Image Formation with a Lens

A positive lens produces an image by refracting light so that all the light

* When photographing relatively close subjects, the value of f should be determined by substituting the object distance (u) and the image distance (v) in the formula $1/f = 1/u + 1/v$.

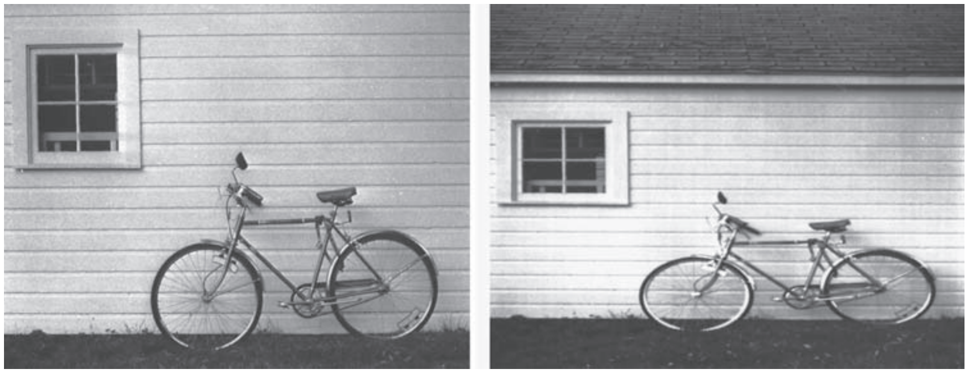


Figure 4-4 An anamorphic pinhole photograph (right) made with a vertical slit placed 1.5 times as far from the film as a horizontal slit. The comparison photograph was made with a camera lens.

Positive lenses are thicker in the center than at the edges. Negative lenses will not form real images that can be recorded on film.

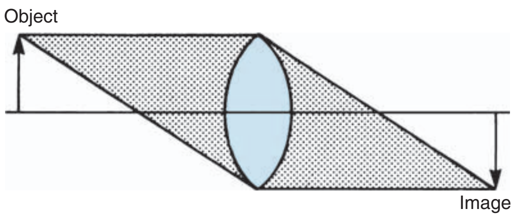


Figure 4-5 Image formation with a positive lens.

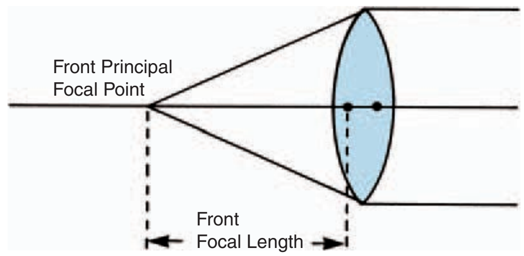


Figure 4-7 The front focal length is found by reversing the direction of light through the lens.

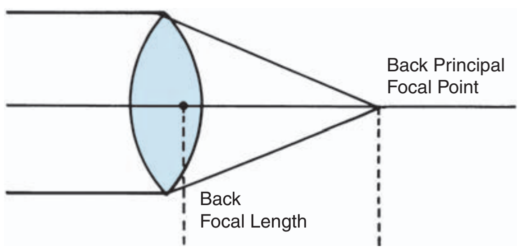


Figure 4-6 The back focal length is the distance between the back nodal point and the image of an infinitely distant object.

rays falling on the front surface of the lens from an object point converge to a point behind the lens (see Figure 4-5). If the object point is at infinity or a large distance, the light rays will enter the lens traveling parallel to each other, and the image point where they come to a focus is referred to as the *principal focal point*. The focal length can then be determined by measuring the distance from the principal focal point to the back nodal point—roughly the middle of a single-element lens (see Figure 4-6). Reversing the direction of light through the lens with a distant object on the right produces a second principal focal point and a second focal length to the left of the lens, as well as a second nodal point (see Figure 4-7). The two sets of terms are distinguished by the adjectives object (or front) and image (or back)—for example, front principal focal point and back principal focal point.

All positive lenses are thicker at the center than at the edges and must have one convex surface, but the other surface can be convex, flat, or concave (see Figure 4-8). The curved surfaces are usually spherical, like the outside (convex) or inside (concave) surface of a hollow ball. Actually, this is not the best shape for forming a sharp image, but it has been widely used because lenses having flat and spherical surfaces are easier to mass produce than those having other curved surfaces, such as parabolic. If the curvature of a spherical lens surface is extended to

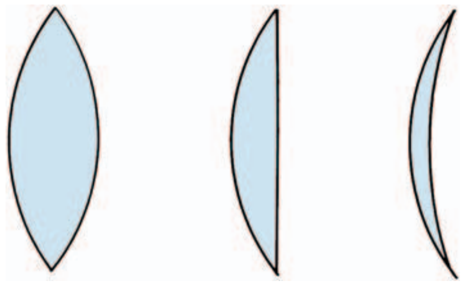


Figure 4-8 Three types of positive lenses: biconvex (left), plano-convex (center), and positive meniscus (right).

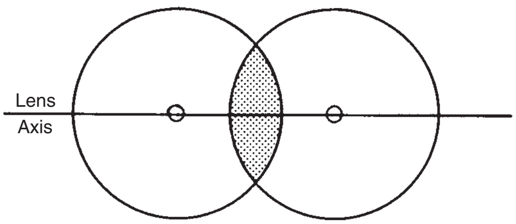


Figure 4-9 The lens axis is a straight line through the centers of curvature of the lens surfaces.

produce a complete sphere, the center of that sphere is then identified as the center of curvature of the lens surface. A straight line drawn through the two centers of curvature of the two lens surfaces is identified as the lens axis (see Figure 4-9). If one of the surfaces is flat, the lens axis is a straight line through the one center of curvature and perpendicular to the flat surface.

The *optical center* of a lens is a point on the lens axis where an off-axis undeviated ray of light crosses the lens axis. All rays of light that pass through the optical center are undeviated—that is, they leave the lens traveling parallel to the direction of entry (see Figure 4-10). Object distance and image distance can be measured to the optical center when great precision is not needed—but when precision is required the object distance is measured from the object to the front (or object) nodal point, and the image distance is measured to the back (or image) nodal point.

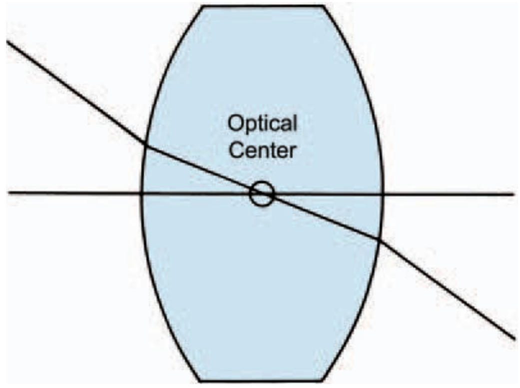


Figure 4-10 All rays of light passing through the optical center leave the lens traveling parallel to the direction of entry.

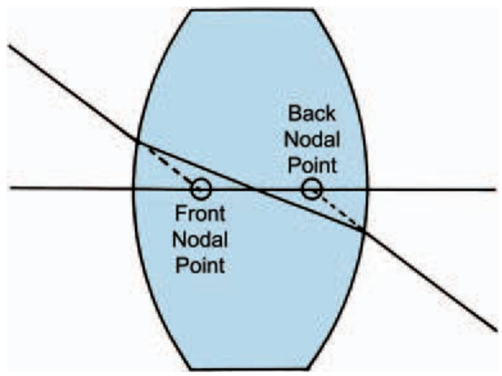


Figure 4-11 The nodal points can be located by extending the entering and departing parts of an undeviated ray of light in straight lines until they intersect the lens axis.

The *front nodal point* can be located on a drawing by extending an entering undeviated ray of light in a straight line until it intersects the lens axis, and the *back nodal point* by extending the departing ray of light backward in a straight line until it intersects the lens axis, as shown in Figure 4-11. A convention (which is not always observed) is to place objects to the left of lenses in drawings and images to the right, so that the light travels in the same direction that our eyes move when reading.

Manufacturers do not mark nodal points on lenses, but they can be located with a simple experiment.

Nodal points can also be located experimentally with lenses. The lens is first placed in a nodal slide, which is a device that enables a lens to be pivoted at various positions along its axis.

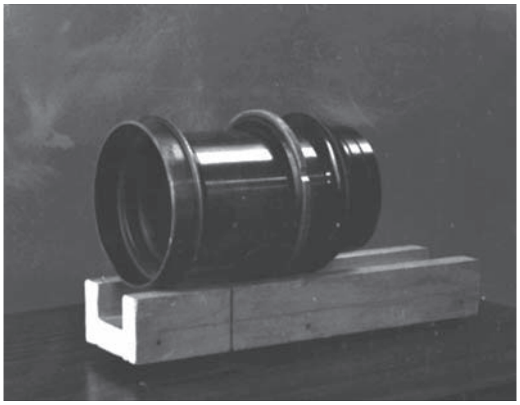


Figure 4-12 A simple nodal slide. The line on the side identifies the location of the pivot point on the bottom.

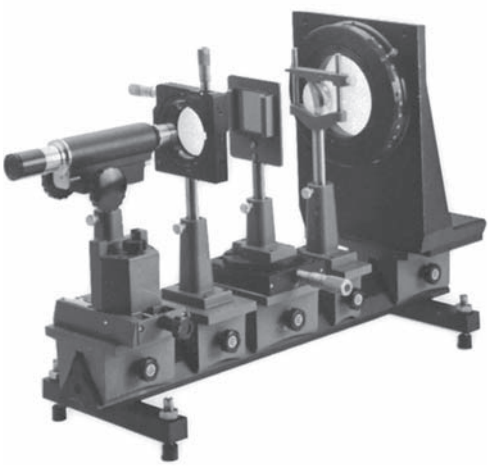


Figure 4-13 A professional optical bench, which permits the aerial image formed by a lens to be examined with a microscope.

For crude measurements, a simple trough with a pivot on the bottom is adequate (see Figure 4-12). Professional optical benches are used when greater precision is required (see Figure 4-13). The lens is first focused on a distant light source or the equivalent using a collimator with a light source placed at an appropriate closer distance, with the front of the lens facing the light source. The lens is then pivoted from side to side while the image is observed. If the image does not move as the lens is pivoted, the lens is being pivoted about its *back (image) nodal point*. If the image does move, however, the lens is moved either toward or away from the light source, the image is brought into focus by moving the focusing screen or the microscope, and the lens is again pivoted. This procedure is repeated until the image remains stationary when the lens is pivoted. The *front (object) nodal point* is determined the same way with the lens reversed so that the front of the lens is facing the image rather than the light source. Knowledge of the location of the nodal points can be useful, and it is unfortunate that the manufacturers of photographic lenses do not provide the locations of the two nodal points on their lenses.

Four practical applications for knowledge of the location of the nodal points are:

1. When accuracy is required, the object distance must be measured from the object to the front nodal point, and the image distance from the image to the back nodal point. Accurate determination of the focal length requires measuring the distance from the sharp image of a distant object to the back nodal point. Measurements to the nodal points are also made when using lens formulas to determine image size and scale of reproduction (see Figure 4-14). With conventional lenses that are relatively thin, little error will be introduced by measuring to the physical center of the lens rather than to the appropriate nodal point. With thick lenses and some lenses of special design—such as telephoto, retrofocus, and zoom lenses—considerable error can be introduced by measuring to the center of the lens. With these types of lenses, the nodal points can be some distance from the physical center of the lens, and may even be in front of or behind the lens. When distances

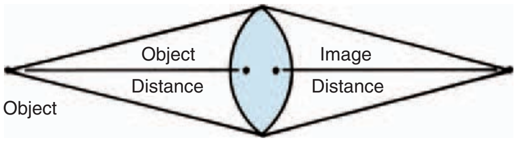


Figure 4-14 For an object point on the lens axis, object distance is measured to the front nodal point, and image distance is measured from the image to the back nodal point.

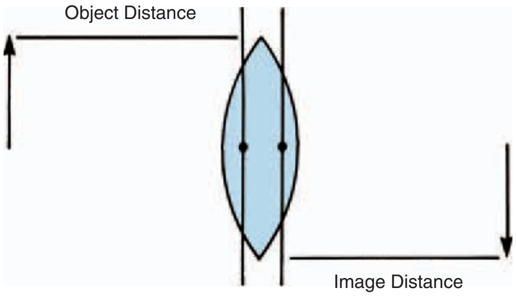


Figure 4-15 For an object point off the lens axis, object and image distances are measured in a direction that is parallel to the lens axis, to the corresponding nodal planes.

are measured for objects or images that are not on the lens axis, the correct procedure is to measure the distance parallel to the lens axis to the appropriate nodal plane rather than to the nodal point. The *nodal plane* is a plane that is perpendicular to the lens axis and that includes the nodal point (see Figure 4-15).

2. If a view-camera lens can be mounted on the camera so that it tilts and swings about the rear nodal point, the image will remain in the same position on the ground glass as these adjustments are made to control the plane of sharp focus. Otherwise the image will move up or down as the lens is tilted and sideways as it is swung, requiring realignment of the camera to restore the original composition. Unfortunately, little consideration is given to this factor in the design of most view cameras and the fact that the nodal points are at different positions with various types of lenses complicates the task. Although a sliding adjustment, as on a nodal slide, is the ideal solution, some improvement may be obtained with certain lenses by using a recessed lens board, a lens cone, or by reversing the lens standard (on modular view cameras having that feature) to change the position of the lens in relation to the pivot point on the camera (see Figure 4-16).

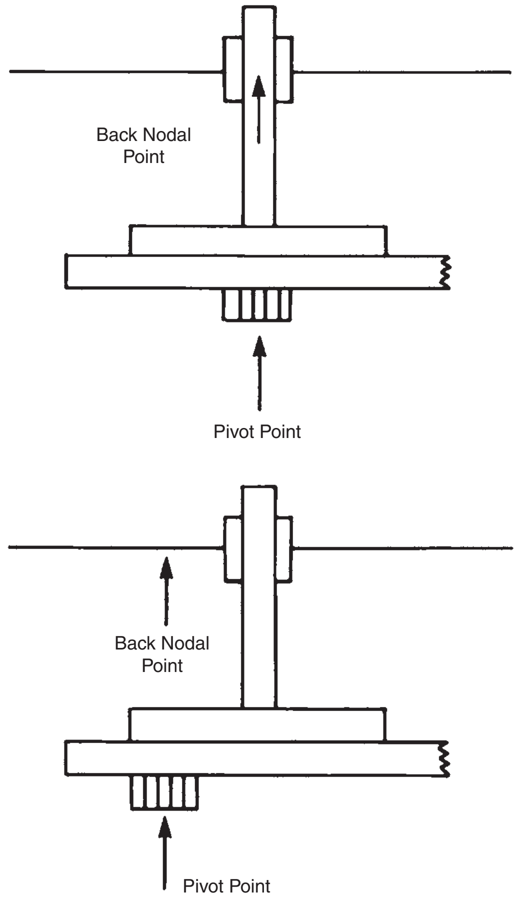


Figure 4-16 Ideally, view cameras would permit the lens pivot point to be adjusted so that all lenses could be rotated about the back nodal point.

3. Panoramic image can be created by capturing multiple digital images and using stitching software to merge the images. If the camera is rotated on the back nodal point, the process of merging the images will be greatly simplified.

4. The task of making graphical drawings to illustrate image formation with lenses is greatly simplified by the use of nodal points and planes rather than lens elements. Whereas lens designers must consider the effect that each surface of each element in a lens has on a large number of light rays, many problems involving image and object sizes and distances can be illustrated and solved by using the nodal planes to represent the lens in the drawing, regardless of the number of lens elements. This procedure will be used in the following section.

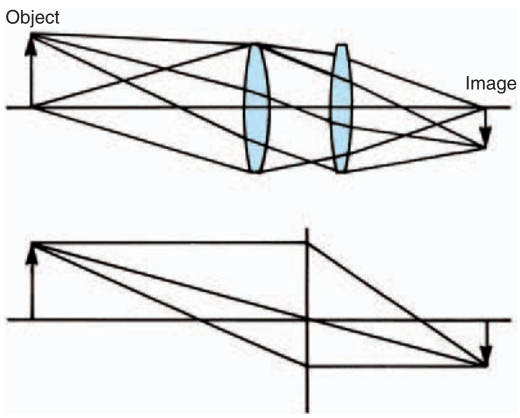


Figure 4-17 Graphical drawings to show image formation using the lens elements (top) and the simpler thin-lens procedure (bottom).

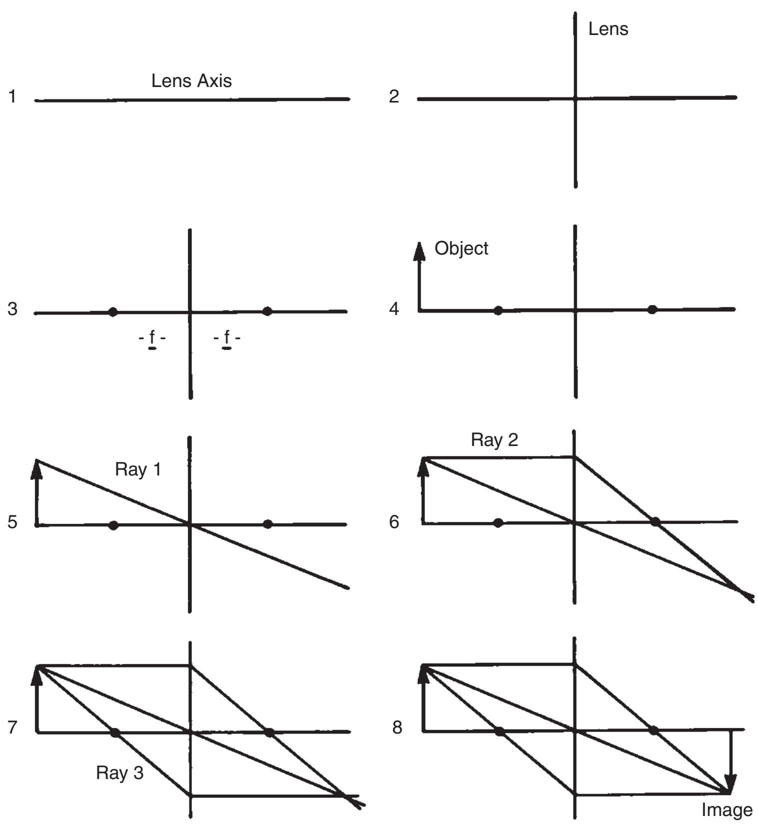


Figure 4-18 Making an actual-size or scale graphical drawing in eight steps.

Graphical Drawings

Graphical drawings are useful in that they not only illustrate image formation with lenses in simplified form, but they can be used as an alternative to mathematical formulas to solve problems involving image formation. The two drawings in Figure 4-17 show a comparison between the use of lens elements and the use of nodal planes. In the so-called thin-lens treatment, the two nodal planes are considered to be close enough to each other so that they can be combined into a single plane without significant loss of accuracy. If the drawing is to be used to solve a problem, rather than as a schematic illustration of image formation, the drawing must be made either actual size or to a known scale. The original drawing in Figure 4-18 was actual size, but the reproduction is smaller. The steps involved in making a graphical drawing are:

1. Draw a straight horizontal line to represent the lens axis.
2. Draw a straight vertical line to represent the lens.
3. Place marks on the lens axis one focal length to the left and one focal length to the right of the lens. In this example, the focal length was 1 inch.
4. Draw the object at the correct distance from the lens. In this example, the object was 2 inches tall and was located 2 inches from the lens.
5. Draw the first ray of light from the top of the object straight through

the optical center of the lens—that is, the intersection of the lens axis and the nodal plane.

6. Draw the second ray, on a parallel to the lens axis, to the nodal plane, then through the back principal focal point.
7. Draw the third ray through the front principal focal point to the nodal plane, then parallel to the lens axis.
8. The intersection of the three rays represents the image of the top of the object. Draw a vertical line from that intersection to the lens axis to represent the entire (inverted) image of the object.

With a ruler, we can determine the correct size and position of the image from the original drawing. The image size was 2 inches and the image distance was 2 inches. From this we can generalize that placing an object two focal lengths in front of any lens produces a same-size image two focal lengths behind the lens.

This same drawing could be used as a one-quarter-scale drawing of a 4-inch focal length lens with an 8-inch-tall object located at an object distance of 8 inches. To determine the image size and image distance, the corresponding dimensions on the drawing are multiplied by 4 to compensate for the drawing's scale. Thus the image size is 2 inches × 4 = 8 inches, and the image distance is 2 inches × 4 = 8 inches.

Changing the distance between the object and the lens produces a change in the position where the image is formed. The relationship is an inverse one, so that as the object distance decreases, the image distance increases. Since the two distances are interdependent and interchangeable, they are commonly referred to as *conjugate distances*. Image size also changes as the object and image distances change.

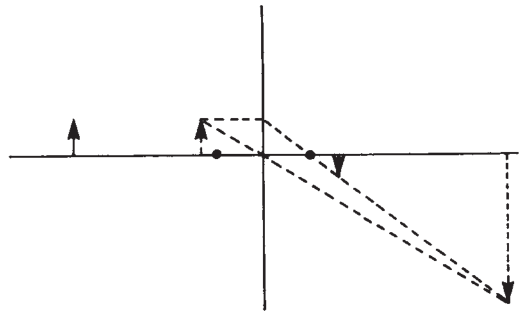


Figure 4-19 Moving an object closer to the lens results in an increase in both image distance and image size.

Moving an object closer to the lens results in an increase in both the image distance and the image size. These relationships are illustrated in Figure 4-19.

The closest an object can be placed to a lens and still obtain a real image is theoretically slightly more than one focal length. Placing an object at exactly one focal length from the lens causes the light rays from an object point to leave the lens traveling parallel to each other so that we can think of an image only as being formed at infinity. In practice, the closest an object can be placed to a camera lens and still obtain a sharp image is determined by the maximum distance the film or sensor can be placed from the lens. Problems of this type can be solved with graphical drawings. If the maximum image distance is 3 inches for a camera equipped with a 2-inch focal length lens, an actual-size or scale drawing is made starting with the image located 3 inches to the right of the lens. Three rays of light are then drawn back through the lens, using the same rules as before, to determine the location of the object.

Simple graphical drawings can be used to solve practical problems involving image size, scale of reproduction, and image and object distances.

With lenses that are too thick to be considered as thin lenses, or where greater accuracy is required, only small modifications of the thin-lens treatment are required. If it is known

The angle of coverage of a lens must be at least as large as the angle of view of the lens-camera combination.

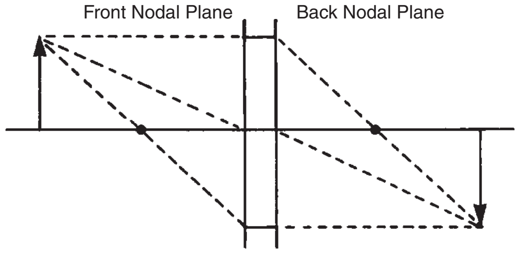


Figure 4-20 The nodal planes are separated by an appropriate distance for thick-lens graphical drawings.

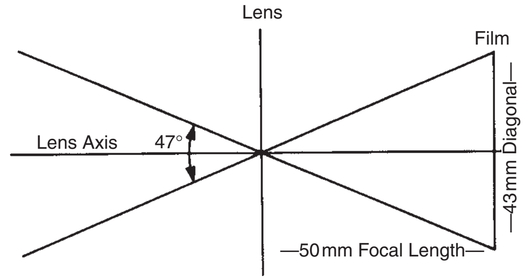


Figure 4-21 The angle of view of a lens-film combination can be determined by drawing a line with the length equal to the film diagonal at a distance of one focal length from the lens. The angle formed by the extreme rays of light can be measured with a protractor.

that the front and back nodal planes are separated by a distance of 1 inch in a certain lens, two vertical lines are drawn on the lens axis to represent the two nodal planes, separated by the appropriate actual or scale distance. The three rays of light are drawn from an object point to the front nodal plane, as before, but they are drawn parallel to the lens axis between the two nodal planes before they converge to form the image (see Figure 4-20).

Angle of view can be determined with graphical drawings in addition to image and object distances and sizes. Angle of view is a measure of how much of the scene will be recorded on the light-sensitive material as determined by the lens focal length and the film or sensor size. Angle of view is usually determined for the diagonal of the film or sensor, which is the longest dimension, although two angles of view are sometimes specified, one for the film's or sensor's vertical dimension and one for the horizontal dimension. A horizontal line is drawn for the lens axis and a vertical line is drawn to represent the nodal planes, as with the thin-lens treatment above. A second vertical line is drawn one focal length (actual or scale distance) to the right of the nodal planes. The second vertical line represents the film or sensor diagonal, so it must be the correct actual or scale length.

The drawing in Figure 4-21 represents a 50-mm focal length lens on a 35-mm camera, where the diagonal of the image area is approximately 43 mm. Lines drawn from the rear nodal point (that is, the intersection of the nodal planes and the lens axis) to opposite corners of the film or sensor form an angle that can be measured with a protractor. No compensation is necessary for the drawing's scale, since there are 360° in a circle no matter how large the circle is drawn. The angle of view in this example is approximately 47°.

Two other focal length lenses, 15 mm and 135 mm, are represented in the drawing in Figure 4-22. The measured angles of view are approximately 110° and 18°. It is apparent from these drawings that using a shorter focal length lens on a camera will increase the angle of view, whereas using smaller film, as in using a reducing back on a large-format camera, will decrease the angle of view. Angle of view is determined with the film or sensor placed one focal length behind the lens, which corresponds to focusing on infinity. When a camera is focused on nearer objects, the lens-to-film or sensor distance increases, and the effective angle of view decreases.

Graphical drawings are especially helpful for beginning photographers

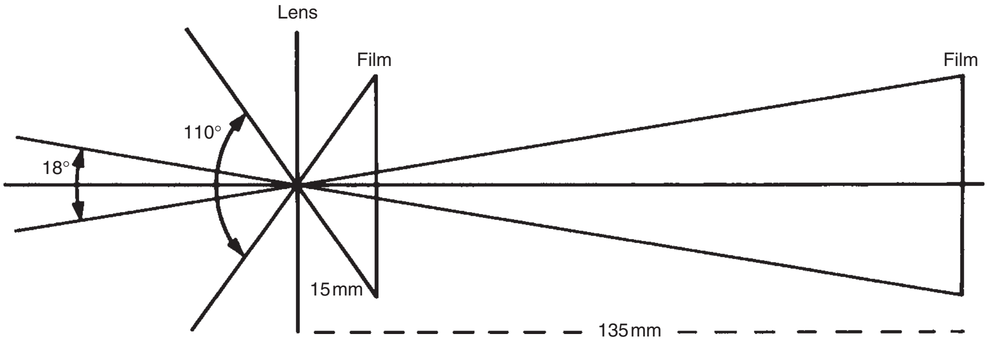


Figure 4-22 Angles of view for 15-mm and 135-mm focal length lenses with 35-mm film.

because they make it easy to visualize the relationships involved. With experience, it becomes more efficient to solve problems relating to distances and sizes using mathematical formulas. Most problems of this nature that are encountered by practicing photographers can be solved by using these four simple formulas:

1. $1/f = 1/u + 1/v$
2. $R = v/u$
3. $R = (v - f)/f$
4. $R = f/(u-f)$

where

f = focal length
u = object distance
v = image distance
R = scale of reproduction, which is image size/object size, or I/O.

The focal length of an unmarked lens can be determined with formula 1 by forming a sharp image of an object, measuring the object and image distances, and solving the formula for f. Thus, if the object and image distances are both 8 inches, the focal length is 4 inches. The formula illustrates the inverse relationship between the conjugate distances u and v, whereby moving a camera closer to an object requires increasing the lens-to-film or lens-to-sensor distance to keep the image in sharp focus.

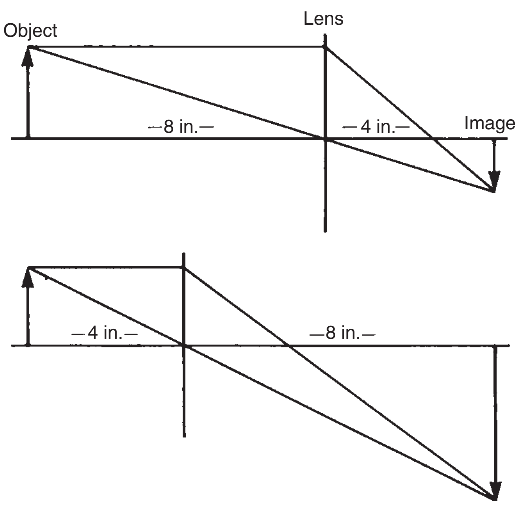


Figure 4-23 Since the object and image distances are interchangeable, sharp image can be found with a lens in two different positions between object and film or sensor.

It also illustrates that u and v are interchangeable, which means that sharp images can be formed with a lens in two different positions between an object and the film or sensor. For example, if a sharp image is formed when a lens is 8 inches from the object and 4 inches from the film or sensor, another (and larger) sharp image will be formed when the lens is placed 4 inches from the object and 8 inches from the film or sensor (see Figure 4-23). Exceptions to the statement that sharp images can be formed with a lens in two different positions are (a) when the object and image distances are the same, which produces

The scale of reproduction for a photograph is equal to the image size divided by the object size or the image distance divided by the object distance.

Depth of field is the range of distances within which objects are imaged with acceptable sharpness.

an image that is the same size as the object, and (b) when an image distance is larger than the maximum bellows extension on the camera, so that the lens cannot be moved far enough away from the image plane to form the second sharp image.

A problem commonly encountered by photographers is determining how large a scale of reproduction (R) can be obtained with a certain camera-lens combination. If a view camera has a maximum bellows extension (v) of 16 inches and is equipped with an 8-inch focal length (f) lens, formula 3 would be selected: $R = (v - f)/f = (16 - 8)/8 = 1$, where the image is the same size as the object. Although to obtain a larger image, a longer focal length lens can be used when the camera cannot be moved closer (see formula 4), a shorter focal-length lens would be used to obtain a larger image in close-up work when the maximum bellows extension is the limiting factor. Replacing the 8-inch lens above with a 2-inch lens would increase the scale of reproduction from $R = 1$ to $R = 7$. $[(16 - 2)/2 = 7]$.

Depth of Field

Camera lenses can be focused on only one object distance at a time. Theoretically, objects in front of and behind the object distance that is focused on will not be imaged sharply on the film. In practice, acceptably sharp focus is seldom limited to a single plane. Instead, objects somewhat closer and farther away appear sharp. *Depth of field* is defined as the range of object distances within which objects are imaged with acceptable sharpness. Depth of field is not limited to the plane focused on because the human eye has limited resolving power, so that a circle up to a certain size appears as a point (see Figure 4-24). The largest circle that appears as a point is referred to as the *permissible circle of confusion*.

Permissible Circle of Confusion

The size of the largest circle that appears as a point (circle of confusion) depends upon viewing distance. For this reason, permissible circles of confusion

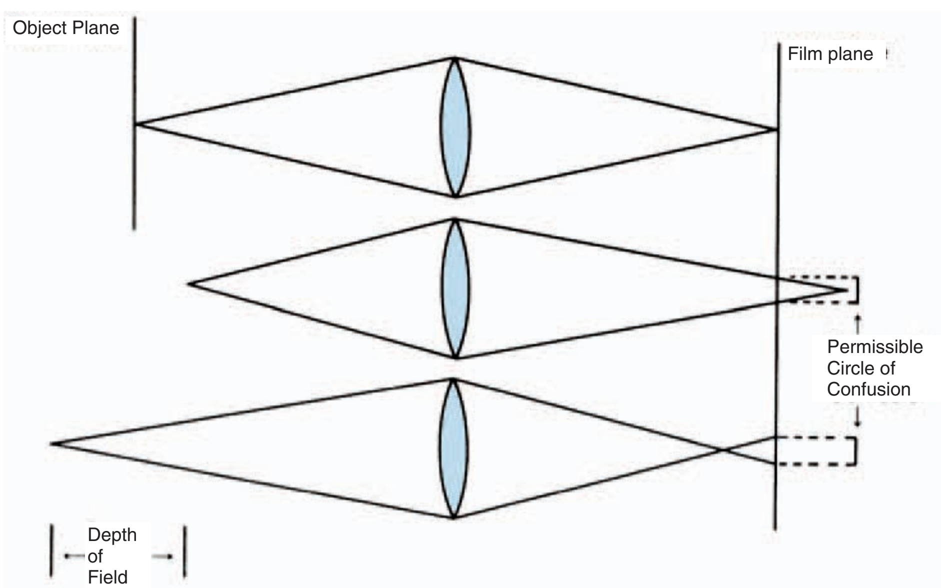


Figure 4-24 Depth of field is the range of distances within which objects are imaged with acceptable sharpness. At the limits, object points are imaged as permissible circles of confusion.

are generally specified for a viewing distance of 10 inches, and 1/100 inch is commonly cited as an appropriate value for the diameter. Even at a fixed distance, the size of the permissible circle of confusion will vary with such factors as differences in individual eyesight, the tonal contrast between the circle and the background, the level of illumination, and the viewer's criteria for sharpness. Nevertheless, when a lens manufacturer prepares a depth-of-field table or scale for a lens, these variables must be ignored. A single value is selected for the permissible circle of confusion that seems appropriate for the typical user of the lens. Although many photographic books that include the subject of depth of field accept 1/100 inch as being appropriate, there is less agreement among lens manufacturers. A study involving a small sample of cameras designed for advanced amateurs and professional photographers revealed that values ranging from 1/70 to 1/200 inch were used—approximately a 3:1 ratio. Two different methods will be considered for evaluating depth-of-field scales and tables for specific lenses.

One procedure is to photograph a flat surface that has good detail at an angle of approximately 45°, placing markers at the point focused on and at the near and far limits of the depth of field as indicated by the depth-of-field scale or table, as shown in Figure 4-25. The first photograph should be made at an intermediate *f*-number, with additional exposures bracketing the *f*-number one and two stops on both sides, with appropriate adjustments in the exposure time. A variation of this procedure is to use three movable objects in place of the flat surface, focusing on one and placing the other two at the near and far limits of the depth of field as indicated by the scale or table.

Figure 4-25 Depth-of-field scales and tables can be checked by photographing an object at an angle with markers placed at the point focused on and at the indicated near and far limits of the depth of field. A 6 × 8-inch or larger print should be made so that it can be viewed from the "correct" viewing distance. (Photograph by Oscar Durand, Photojournalism student, Rochester Institute of Technology.)

To judge the results, 6 × 8-inch or larger prints should be made without cropping and viewed from a distance equal to the diagonal of the prints. The diagonal of a 6 × 8-inch print is 10 inches, which is considered to be the closest distance at which most people can comfortably view photographs or read. If the photograph made at the *f*-number specified by the depth-of-field scale or table has either too little or too much depth of field when viewed at the correct distance, the photograph that best meets the viewer's expectation should be identified from the bracketing series. A corresponding adjustment can be made when using the depth-of-field scale or table in the future.

When a camera is focused on the hyperfocal distance, everything should appear sharp in the photograph from infinity to one-half the hyperfocal distance.

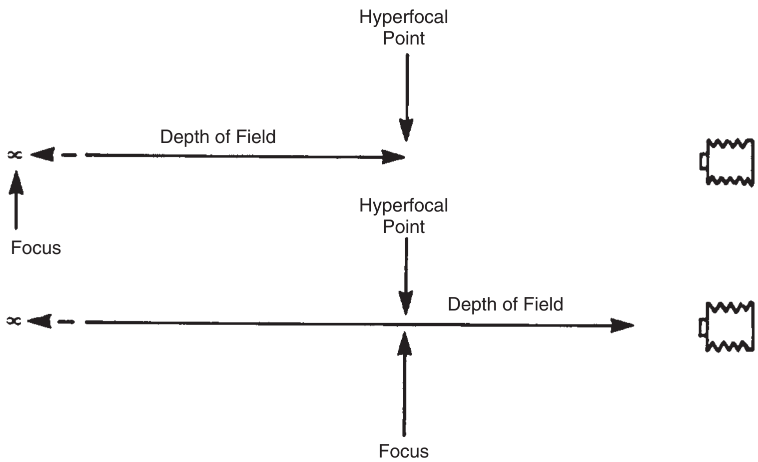


Figure 4-26 The hyperfocal distance is the closest distance that appears sharp when a lens is focused on infinity (top), or the closest distance that can be focused on and have an object at infinity appear sharp (bottom).

Figure 4-27 The hyperfocal distance can be determined from a depth-of-field scale either by focusing on infinity and noting the near distance sharp at the specified *f*-number (top) or by setting infinity opposite the far-distance sharp marker and multiplying the near distance sharp by two (bottom). (Photograph by James Craven, Imaging and Photographic Technology student, Rochester Institute of Technology.)

The second procedure involves determining the diameter of the permissible circle of confusion used by the lens manufacturer in calculating the depth-of-field scale or table. It is not necessary to expose any film with this procedure. Instead, substitute values for the terms on the right side of the formula $C = f^2/(N \times H)$ and solve for C, where C is the diameter of the permissible circle of confusion on the film, f is the focal length of the lens, N is any selected *f*-number, and H is the hyperfocal distance at that *f*-number.

Hyperfocal distance can be defined in either of two ways: (a) the closest distance that appears sharp when a lens is focused on infinity, or (b) the closest distance that can be focused on while having an object at infinity appear sharp. Although the two procedures are different, the results will be essentially the same. When a lens is focused on the hyperfocal distance, the depth of field extends from infinity to one-half the hyperfocal distance (see Figure 4-26). If $f/22$ is selected as the *f*-number with a 2-inch (50-mm) focal length lens, the hyperfocal distance can be determined either from a depth-of-field table or from a depth-of-field scale on the lens or camera by noting the near distance sharp at $f/22$ when the lens is focused on infinity. (If the near-limit marker on a DOF scale falls between two widely separated numbers, making accurate estimation difficult, set infinity opposite the far-limit marker, as shown in Figure 4-27, and multiply the distance opposite the near-limit marker by two.)

Since the circle of confusion is commonly expressed as a fraction of an inch, the hyperfocal distance and the focal length must be in inches. The hyperfocal distance at f/22 for the lens illustrated is 21 feet or 252 inches. Substituting these values in the formula $C = f^2/(N \times H)$ produces $2^2/22 \times 252$ or 1/1,386 inch. This is the size of the permissible circle of confusion on the negative, but a 35-mm negative must be magnified six times to make a 6 × 8-inch print to be viewed at 10 inches. Thus, 6 × 1/1,386 = 1/231 inch, or approximately half as large a permissible circle of confusion as the 1/100-inch value commonly used.

Note that the size of the permissible circle of confusion used by a lens

manufacturer in computing a depth-of-field table or scale tells us nothing about the quality of the lens itself. The manufacturer can arbitrarily select any value, and in practice a size is selected that is deemed appropriate for the typical user of the lens. If a second depth-of-field scale is made for the lens in the preceding example based on the new calculated circle with a diameter of 1/200 inch, the new scale would indicate that it is necessary to stop down only to *f*/11 in a situation where the original scale specified *f*/22. Lens definition, however, is determined by the quality of the image for the object focused on, not the near and far limits of the indicated depth of field.

Depth-of-Field Controls

Photographers have three controls over depth of field: *f*-number, object distance, and focal length. Since viewing distance also affects the apparent sharpness of objects in front of and behind the object focused on, it is generally assumed that photographs will be viewed at a distance about equal to the diagonal of the picture. At this distance, depth of field will not be affected by making different-size prints from the same negative. For example, the circles of confusion at the near and far limits of the depth of field will be twice as large on a 16 × 20-inch print as on an 8 × 10-inch print from the same negative, but the larger print would be viewed from double the distance, making the two prints appear to have the same depth of field. If the larger print were viewed from the same distance as the smaller print, it would appear to have less depth of field. Cropping when enlarging will decrease the depth of field because the print size and viewing distance will not increase in proportion to the magnification.

Photographers can change the depth of field in photographs by changing *f*-number, the object distance, or the focal length of the camera lens.

Depth of Field and *F*-Number

The relationship between *f*-number and depth of field is a simple one, doubling the *f*-number doubles the depth of field. In other words, depth of field is directly proportional to the *f*-number, or $D_1/D_2 = N_1/N_2$. Thus, if a lens has a range of *f*-numbers from *f*/2 to *f*/22, the ratio of the depth of field at these settings would be $D_1/D_2 = (f/22)/(f/2) = 11/1$. Changing the *f*-number is generally the most convenient method of controlling depth of field, but occasionally insufficient depth of field is obtained with a lens stopped down to the smallest diaphragm opening or too much depth of field is obtained with a lens wide open. In these circumstances other controls must be considered.

Depth of field is directly proportional to the *f*-number.

Depth of Field and Object Distance

Depth of field increases rapidly as the distance between the camera and the subject increases. For example, doubling the object distance makes the depth of field four times as large. The differences in depth of field with very small and very large object distances are dramatic. In photomacrography, where the camera is at a distance of two focal lengths or less from the subject, the depth of field at a large aperture sometimes appears to be confined to a single plane (see Figure 4-28).

At the other extreme, by focusing on the hyperfocal distance, depth of field extends from infinity to within a few feet of the camera with some lenses (see Figure 4-29). The mathematical relationship between depth of field and

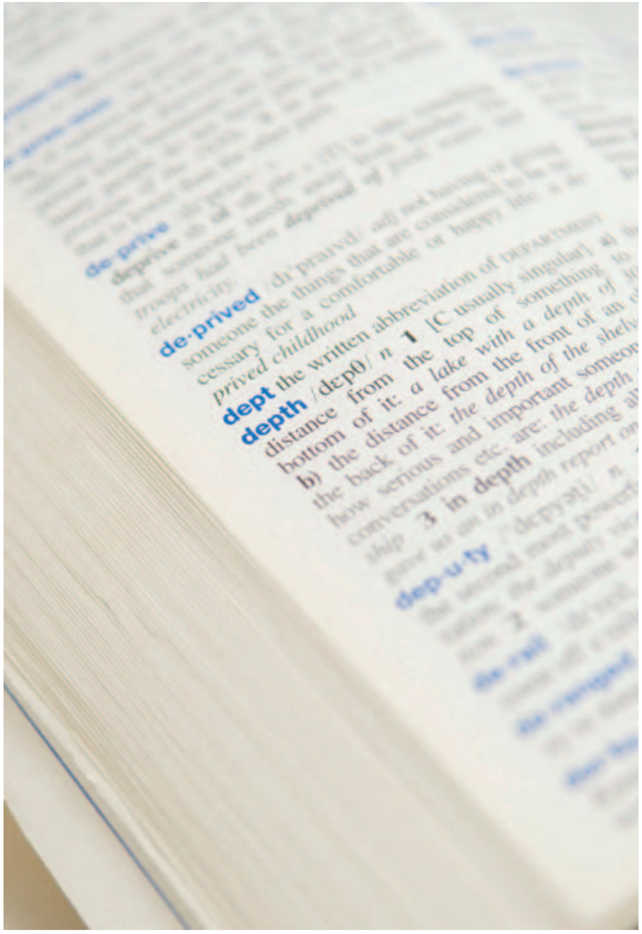


Figure 4-28 Since depth of field varies in proportion to the object distance squared, photographs made at a scale of reproduction of 1:1 and larger tend to have a shallow depth of field. (Photograph by Oscar Durand, Photojournalism student, Rochester Institute of Technology.)

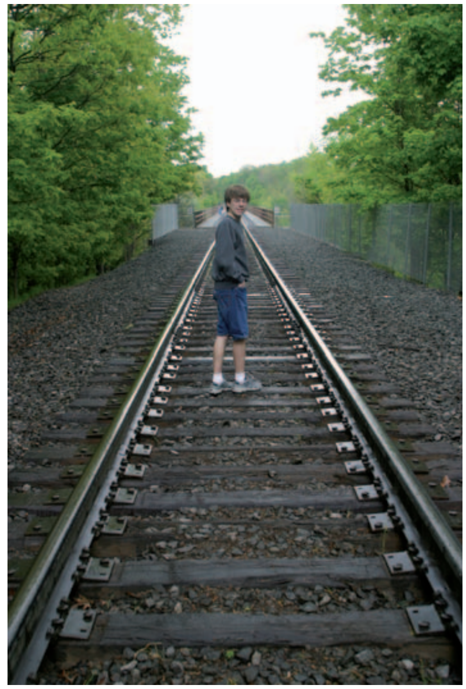


Figure 4-29 Focusing on the hyperfocal distance produces a depth of field that extends from infinity to one-half the hyperfocal distance. (Photograph by Nanette L. Salvaggio.)

object distance (provided the object distance does not exceed the hyperfocal distance) is represented by the formula $D_1/D_2 = U_1^2/U_2^2$. For example, if two photographs are made with the camera 5 feet and 20 feet from the subject, the ratio of the depths of field will be

$$\frac{D_1}{D_2} = \frac{20^2}{5^2} \quad \text{or} \quad \left(\frac{20}{5}\right)^2 = \frac{16}{1}$$

If, however, object distance is increased to obtain a larger depth of field when a camera lens cannot be stopped down far enough, it is necessary to take into account the enlarging and cropping required to obtain the same image size as with the camera in the original position. There is still a net gain in depth of field in moving the camera farther from the subject, even though some of the increase is lost when the image is cropped in printing. The net gain is represented by the formula $D_1/D_2 = U_1/U_2$, which is the same as the preceding formula with the square sign removed.

Depth of Field and Focal Length

There is an inverse relationship between focal length and depth of field, so as focal length increases, depth of field decreases. Before specifying the relationship more exactly, however, it is necessary to distinguish between situations where the different focal length lenses are used on different format cameras, such as 35-mm and 8 × 10-inch, and where the lenses

are used on the same camera. When a large-format camera and a small-format camera are each equipped with a normal focal-length lens, that is, a lens with a focal length about equal to the film diagonal, the depth of field will be inversely proportional to the focal length. For example, a 2-inch (50-mm) focal length lens on a 35-mm camera will produce about six times the depth of field of a 12-inch (305-mm) lens on an 8 × 10-inch camera. Even though enlarging negatives does not affect the depth of field, it is easier to compare the depth of field on two prints when they are the same size. Thus it would be appropriate to make an 8 × 10-inch enlargement from the 35-mm negative and a contact print from the 8 × 10-inch negative. The above relationship of depth of field and focal length is expressed as

$$\frac{D_1}{D_2} = \frac{f_2}{f_1}$$

Using the same two lenses on one camera produces a more dramatic difference in depth of field. It is now necessary to square the focal lengths so that $D_1/D_2 = f_2^2/f_1^2$ Comparing the depth of field produced with 50-mm and 300-mm focal-length lenses on a 35-mm camera, the ratio of the focal lengths is 1:6, and the ratio of the depths of field is 36:1. The great increase in depth of field with the shorter lens evaporates, however, if the camera is moved closer to the subject to obtain the same size image on the film as with the longer lens. In this example, the camera would be placed at distances having a ratio of 1:6 to obtain the same image size with the 50-mm and 300-mm lenses, and we recall that depth of field increases with the distance squared, so that the 36-times increase obtained with the shorter lens would be exactly offset by the reduction in object distance.

There is still a net gain in using a shorter focal-length lens on the same camera if the negative is enlarged and cropped to obtain the same image size and cropping on a print as that produced with a longer lens. This is essentially the same situation as using different format cameras each with a normal focal-length lens.

Depth of Focus

Depth of focus can be defined as the focusing latitude when photographing a two-dimensional subject. In other words, it is the distance the film or sensor plane can be moved in both directions from the optimum focus before the circles of confusion for the image of an object point match the permissible circle of confusion used to calculate depth of field. It is important to note that for depth-of-field calculations it is assumed the image plane occupies a single flat plane, and for depth-of-focus calculations it is assumed that the subject occupies a single flat plane (see Figure 4-30). If a three-dimensional

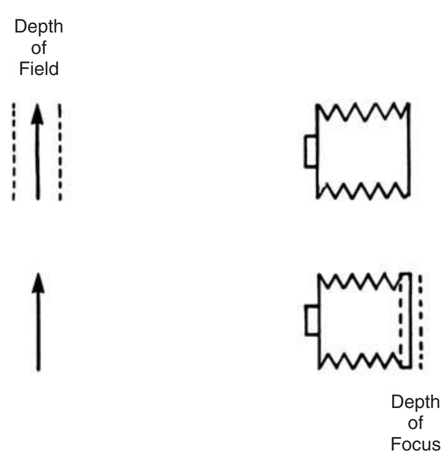


Figure 4-30 Depth-of-field calculations are based on the assumption that the two-dimensional film is in the position of optimum focus (top). Depth-of-focus calculations are based on the assumption that the subject is limited to a two-dimensional plane (bottom).

A 50-mm focal-length camera lens produces four times as much depth of field as a 100-mm focal-length lens, with all other conditions remaining the same.

Depth of focus refers to the focusing latitude when photographing a two-dimensional subject.

The tilt and swing adjustments on view cameras provide control over image shape and the angle of the plane of sharp focus.

object completely fills the depth-of-field space, there is only one position for the film or sensor, and there is in effect no depth of focus and no tolerance for focusing errors.

With a two-dimensional subject, the depth of focus can be found by multiplying the permissible circle of confusion by the *f*-number by 2. Thus, using 1/200-inch for the permissible circle of confusion on a 6 × 8 inch print or 1/1,200 inch on a 35-mm negative, the depth of focus is $C \times N \times 2 = 1/1{,}200 \times f/2 \times 2 = 1/300$ inch. It can be seen from this formula that depth of focus varies in direct proportion to the *f*-number, as does depth of field.

Whereas depth of field decreases as a camera is moved closer to the subject, depth of focus increases. This is because as the object distance decreases, the lens-to-film or sensor distance must be increased to keep the image in sharp focus, and this increases the effective *f*-number. It is the effective *f*-number, not the marked *f*-number, that is used in the formula.

Although increasing focal length decreases depth of field, it has no effect on depth of focus. The explanation is that at the same *f*-number the diameter of the effective aperture and the lens-to-film or sensor distance both change in proportion to changes in focal length so that the shape of the cone of light falling on the film or sensor remains unchanged. Because focal length does not appear in the formula $C \times N \times 2$, it has no effect on depth of focus.

Although changing film or sensor size would not seem to affect depth of focus, using a smaller film reduces the correct viewing distance and, therefore, the permissible circle of confusion. Substituting a smaller value for C in the formula $C \times N \times 2$ reduces the depth of focus.

View-Camera Movements

The basic view-camera movements include (1) an adjustment of the distance between the lens and the film to permit focusing on objects over a wide range of distances and to accommodate lenses having a wide range of focal lengths, (2) vertical and horizontal perpendicular movements of the lens and film to provide control over the positioning of the image on the film without altering image shape or the angle of the plane of sharp focus, and (3) tilt and swing movements of the lens and film to provide control over image shape and the angle of the plane of sharp focus. Some view cameras also have revolving backs that allow the film to be rotated in the film plane to provide angular control of cropping.

Perpendicular Movements

The circular area within which satisfactory image definition can be obtained is called the *circle of good definition*. The circle of good definition is one measure of the covering power of a lens (see Figures 4-31 and 4-32). If the circle of good definition is somewhat larger than the film, it will be possible to select different parts of the image within the circle to record on the film. View cameras typically have

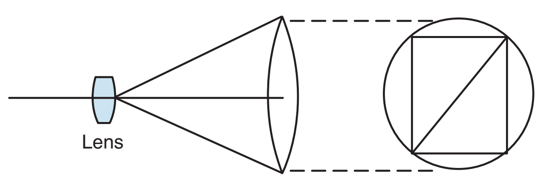


Figure 4-31 The diameter of the circle of good definition of a lens must be at least as large as the diagonal of the film.

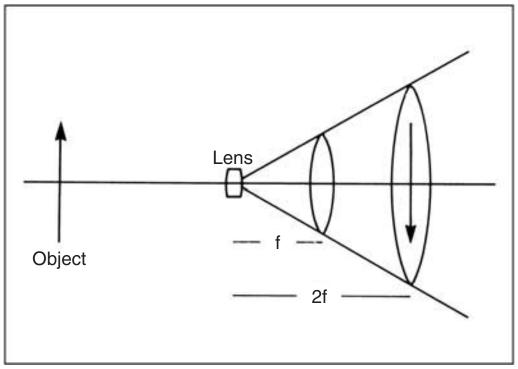


Figure 4-32 Edges of the circle of good definition and the circle of illumination of a camera lens at the maximum aperture (left) and the minimum aperture (right). Stopping down increases the size of the circle of good definition and the abruptness of the transition from the illuminated area to the nonilluminated area.

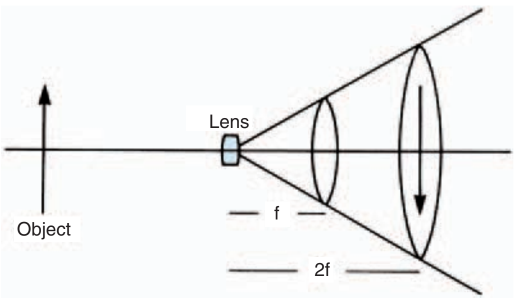


Figure 4-33 Changes in object and image distances do not affect the angle of coverage of a lens.

Figure 4-34 Photographing a book at an angle to show the front edge and one end causes the horizontal lines to converge with increasing distance (top). Swinging the back of the camera parallel to the front edge of the book eliminates the convergence of the horizontal lines in that plane (bottom). (Photographs by Oscar Durand, Photojournalism student, Rochester Institute of Technology.)

rising-falling adjustments to move the lens and/or film up and down, and lateral shifts to move the lens and/or film from side to side.

Angle of coverage is a second measure of the covering power of a lens, and can be determined by drawing straight lines from opposite sides of the circle of good definition to the back nodal point of the lens. Changes in object and image distances affect the size of the circle of good definition, but do not affect the angle of coverage (see Figure 4-33).

Back Movements and Image Shape

When the front of a long building or box-shaped object is photographed at an oblique angle, the near end is taller than the far end in the photograph, and the horizontal lines converge toward the far end. If the back of the camera is swung (that is, rotated about a vertical axis) parallel to the front of the object, the near and far ends will be the same size and the horizontal lines will be parallel in the photograph regardless of the camera-to-object distance (see Figure 4-34). Conversely, the ratio of image sizes and the convergence of the horizontal lines can be increased by swinging the back of the camera in the other direction, away from being parallel to the front of the object.

Swinging and tilting the lens on a view camera will not alter the convergence of subject lines or the shape of the image.

Image shape is controlled by swinging and tilting the back of the camera. Image sharpness can be controlled by altering the angle of either the front or the back

Tilting a camera upward to photograph a tall building causes the vertical subject lines to converge in the photograph for the same reasons as the horizontal lines, since the top of the building is at a greater distance from the camera than the bottom. To make the image lines parallel in this situation, the back is tilted (rotated about a horizontal axis) until it is parallel to the vertical subject lines, and the convergence can be exaggerated by tilting the back in the opposite direction. It would even be possible to make the top of the building appear to be larger than the bottom by overcorrecting, that is, by tilting the back to the vertical position and beyond.

Back Movements and Image Sharpness

In situations where the swing and tilt adjustments on the camera back are not needed to control the convergence of parallel subject lines or to otherwise control image shape, they can be used to control the angle of the plane of sharp focus in object space. Whereas only the back adjustments can be used to control image shape, either the back or lens adjustments can be used to control the angle of the plane of sharp focus. When both image shape and sharpness must be controlled, the back adjustments are used for shape (since there is no other choice) and the lens adjustments are used for sharpness.

Figure 4-35 illustrates that the image of a distant object on the left comes to a focus closer behind the lens than the image of a nearby object on the right, as specified by the lens formula $1/f = 1/u + 1/v$, where the conjugate object and image distances vary inversely. To obtain a sharp image, the back is swung in a direction away from being parallel to the object plane containing the two object points—the opposite direction to that used to prevent convergence of parallel lines in the same object plane.

This relationship of the plane of the subject, the plane of the lens board, and the plane of sharp focus in image space is known as the Scheimpflug rule (see Figure 4-36).

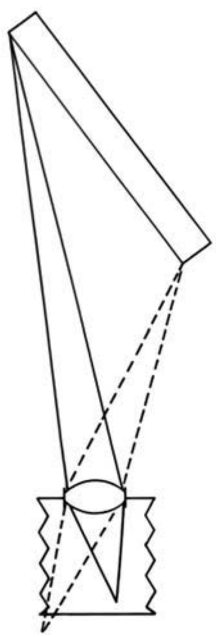


Figure 4-35 When a camera is focused on an intermediate distance, the image of the far end comes to a focus in front of the film, and the image of the near end comes to a focus behind the film.

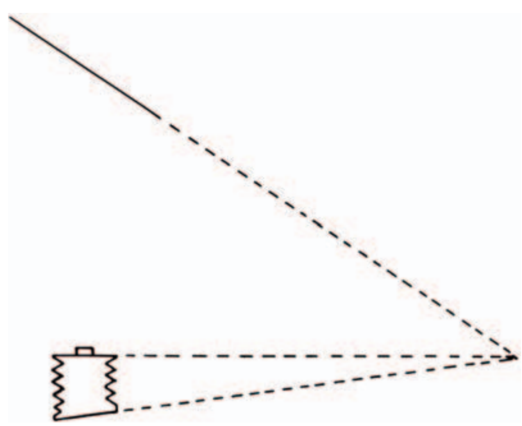


Figure 4-36 The convergence of the planes of the subject, the lens board, and the film illustrates the Scheimpflug rule for controlling the angle of the plane of sharp focus.

Lens Movements and Image Sharpness

The Scheimpflug rule indicates that if the back of the camera is left in the zero position with a subject that is at an oblique angle, the lensboard can be swung (or tilted) to obtain convergence of the three planes at a common location. The lensboard is swung toward a position parallel to the subject plane to obtain a sharp image, whereas the back of the camera was swung in the opposite direction.

Lens Types

Descriptive names applied to different types of camera lenses include normal, telephoto, catadioptric, wide-angle, reversed telephoto (retrofocus), supplementary, convertible, zoom, macro, macro-zoom, process, soft focus, and anamorphic. Considerable variations exist among so-called normal lenses, especially in the characteristics of focal length, speed, image quality, and price. The characteristic most common to normal-type lenses is an angular covering power of about 53°, which is just sufficient to cover the film when the focal length is equal to the film diagonal. The rule of thumb that recommends using a lens having a focal length about equal to the film diagonal is reasonable for normal-type lenses with most cameras, but longer focal-length normal-type lenses should be used with view cameras to provide sufficient covering power to accommodate the camera movements. In the past, many cameras were built with the lens permanently attached, the implication being that one lens should be able to satisfy all picture-taking needs. Most contemporary cameras are constructed so that other lenses can be substituted, enabling photographers to take advantage of the great variety of special-purpose lenses available.

Telephoto Lenses

Telescopes and microscopes were invented to enable us to see distant objects, as well as small objects more clearly. Photographers often want to record larger images of these distant and small objects than can be produced with lenses of normal focal length and design. We know that the image size of a distant object is directly proportional to the focal length. Thus, to obtain an image that is six times as large as that produced by a normal lens, the focal length must be increased by a factor of six, but the lens-to-film distance will also be increased six times unless the lens design is modified. The lens-to-film distance is shorter with telephoto lenses than with normal lenses of the same focal length. Compactness is the advantage of equipping a camera with a telephoto lens rather than a normal-type lens of the same focal length. Photographs made with the two lenses, however, would be the same with respect to image size, angle of view, linear perspective, and depth of field.

The basic design for a telephoto lens is a positive element in front of and separated from a negative element (see Figure 4-37). When a telephoto lens and a normal-type lens of the same focal length are focused on a distant object point, both images will come to a focus one focal length behind the respective back (image) nodal planes; but the lens-to-image distance will be smaller with the telephoto lens. The reason for the reduced lens-to-image distance is that the back nodal plane is located in front of the lens with telephoto lenses rather than near the center, as with normal lenses. It is easy to locate the position

Telephoto lenses have shorter lens-to-film distances than normal-type lenses of the same focal length.

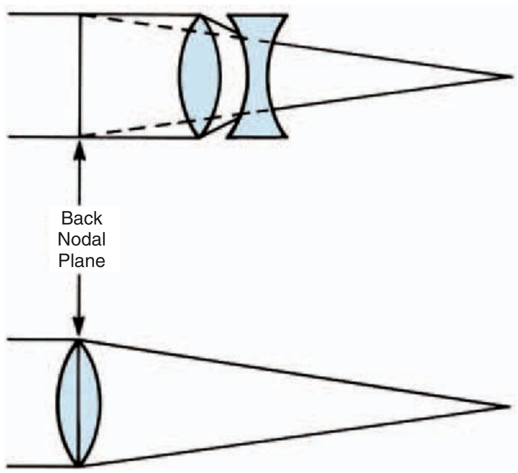


Figure 4-37 The lens-to-film distance is shorter for a telephoto lens (top) than for a normal-type lens (bottom) of the same focal length.

Catadioptric lenses contain mirrors and glass elements.

of the back nodal plane in a ray tracing of a telephoto lens focused on a distant object point, as in Figure 4-37, by reversing the converging rays of light in straight lines back through the lens until they meet the entering parallel rays of light. To determine the position of the back nodal point with an actual telephoto lens, the lens can be pivoted about various positions along the lens axis on a nodal slide until the image of a distant object remains stationary; or the lens and camera can be focused on infinity, whereby the back nodal point will be located exactly one focal length in front of the image plane. The position of the back nodal plane should be noted in relation to the front edge of the lens barrel, since this relationship will remain constant. If the back nodal plane is found to be located 2 inches forward of the front of a telephoto lens, two inches should be added to the distance from the front of the lens to the film any time the image distance (v) is used in a calculation, such as to determine scale of reproduction or the exposure correction for close-up photography. Although telephoto lenses are not generally used for close-up photography, the close-up range begins at an object distance of about ten times the focal length, which can be a considerable distance with a long focal length telephoto lens.

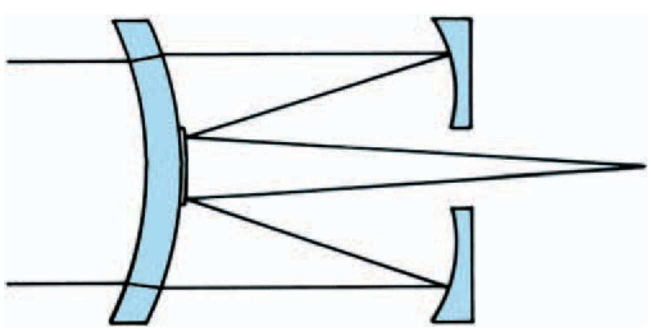


Figure 4-38 Catadioptric lenses make use of folded optics to obtain long focal lengths in relatively short lens barrels.

Catadioptric Lenses

Notwithstanding the shorter lens-to-film distance obtained with telephoto lenses compared to normal lenses of the same focal length, the distance becomes inconveniently large with very long focal-length telephoto lenses. Catadioptric lenses achieve a dramatic improvement in compactness through the use of folded optics. They combine glass elements and mirrors to form the image. The name *catadioptric* is derived from dioptrics (the optics of refracting elements) and catoptrics (the optics of reflecting surfaces). Figure 4-38 illustrates the principle of image formation with a catadioptric lens. A beam of light from a distant point passes through the glass element, except for the opaque circle in the center; it is reflected by the concave mirror and again by the smaller mirror on the back of the glass element, and it passes through the opening in the concave mirror to form the image on the film. The glass element and the opaque stop reduce aberrations inherent in the mirror

system. Additional glass elements are commonly used between the small mirror and the film or sensor.

Location of the image nodal plane and the focal length of a catadioptric lens can be determined by the same methods described above for telephoto lenses. When the converging light rays that form the image on the film are reversed in straight lines on a ray tracing until they meet the entering rays of light, it can be seen that the image nodal plane is located a considerable distance in front of the lens, and the lens-to-image distance is small compared to the focal length (see Figure 4-39).

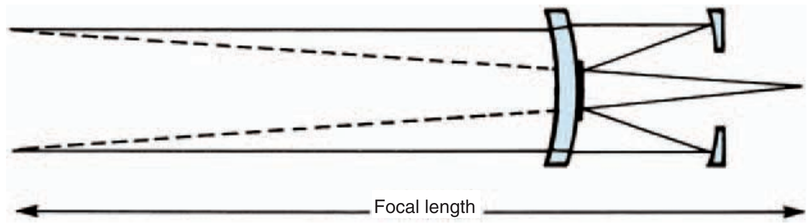


Figure 4-39 The image nodal plane and the focal length of a catadioptric lens can be determined by reversing the converging rays of light that form the image in straight lines until they meet the corresponding entering rays.

Catadioptric lenses are capable of producing images having excellent definition. There are also disadvantages with this type of lens. The long focal length means the lens diameter would have to be very large to match the low *f*-numbers commonplace on lenses of normal design. Since a variable diaphragm cannot be used with this type of lens, exposure must be controlled with the shutter or by using neutral-density filters, and there is no control over depth of field. An additional disadvantage is that *f*-numbers calculated by dividing the focal length by the effective aperture do not take into consideration the light that is blocked by the mirrored spot in the center of the glass element.

Wide-Angle Lenses

Two especially important reasons for substituting a shorter focal-length lens on a camera equipped with a lens of normal focal length and design are (a) the need to include a larger area of a scene in a photograph from a given camera position, and (b) the need to obtain a larger scale of reproduction when photographing small objects and the maximum lens-to-image distance capability of the camera is the limiting factor. In the latter situation, a shorter focal-length lens of normal design can be used satisfactorily because the diameter of the circle of good definition of the lens increases in proportion to the lens-to-image distance, which is necessarily larger for close-up photography and photomacrography. The same shorter focal-length lens would not have sufficient covering power to photograph more distant scenes where the lens-to-image distance is about equal to the focal length.

A wide-angle lens can be defined as a lens having an angular covering power significantly larger than the approximately 53° angle of coverage provided by a normal-type lens, or as having a circle of good definition with a diameter considerably larger than the focal length when focused on infinity (see Figure 4-40). Wide-angle lenses are not restricted to short focal-length lenses. It would be appropriate to use a wide-angle lens with a focal length equal to the film diagonal on a view camera where the extra covering power is needed to accommodate the view camera movements.

There is no distinctive basic design for wide-angle lenses comparable to the arrangement of positive and negative elements in telephoto lenses, except for that of the reversed telephoto wide-angle lenses. Early wide-angle lenses tended toward symmetry

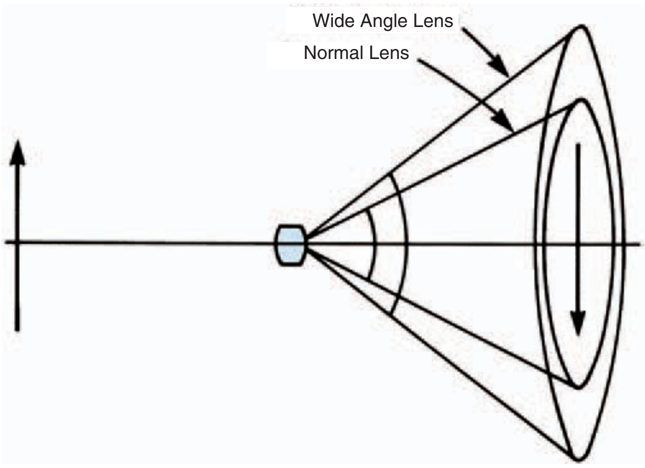


Figure 4-40 The covering power of a wide-angle lens compared to that of a normal-type lens of the same focal length. The images formed by the two lenses would be the same size.

The diameter of the circle of good definition of wide-angle lenses is considerably larger than the focal length.

Reversed telephoto wide-angle lenses are used on single-lens reflex cameras to avoid interference between the lens and the mirror.

about the diaphragm, with few elements, and they usually had to be stopped down somewhat to obtain an image with satisfactory definition. Most, but not all, modern wide-angle lenses have a considerable number of elements, and they generally produce good definition even at the maximum aperture, with much less falloff of illumination toward the corners than the earlier lenses.

Wide-angle lenses of the *fisheye* type are capable of covering angles up to 180°, but only by recording off-axis straight subject lines as curved lines in the image. At this time, rectilinear wide-angle lenses are available that cover an angle of 110° with a 15-mm focal length on a 35-mm camera. There is no minimum angle of coverage that a lens must have to qualify as a wide-angle lens—the label is used at the discretion of the manufacturer. A 35-mm focal-length wide-angle lens for a 35-mm camera, for example, only needs to have a 63° angle of coverage.

Reversed Telephoto Wide-Angle Lenses

Problems may be encountered when using short focal-length wide-angle lenses of conventional design because of the resulting short lens-to-film distances. With view cameras, the short distance between the front and back standards can interfere with focusing or use of the swing, tilt, and other camera movements because of bellows bind. View-camera manufacturers and users have found various ways of avoiding or minimizing these difficulties, for example, by using recessed lens boards with wide-angle lenses and substituting flexible bag bellows for the stiffer accordion type. With single-lens reflex cameras, the placement of a short focal-length lens close to the film plane can interfere with the operation of the mirror, requiring the mirror to be locked in the up position, which makes the viewing system inoperative. The shutter and viewing mechanisms in motion-picture cameras may also prevent short focal-length wide-angle lenses from being placed as close to the film plane as required.

The lens designer's solution to the problems mentioned above is to reverse the arrangement of the elements in a telephoto lens, placing a negative element or group of elements in front of and separated from a positive element or group of elements. This design places the image nodal plane behind the lens (or near the back surface), which in effect moves the lens farther away from the film (see Figure 4-41). Lenses of this type are at different times referred to as reversed telephoto, inverted telephoto, and retrofocus wide-angle lenses. They have largely replaced the more traditional type of wide-angle lenses for small-format reflex cameras, but they

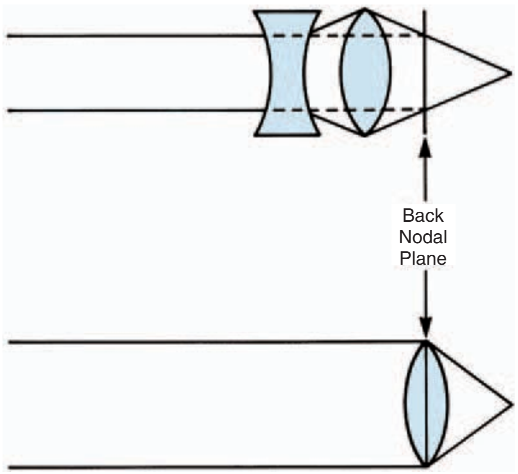


Figure 4-41 The back nodal plane is behind the lens with reversed-telephoto wide-angle lenses, providing a larger lens-to-film distance than for a normal-type lens of the same focal length.

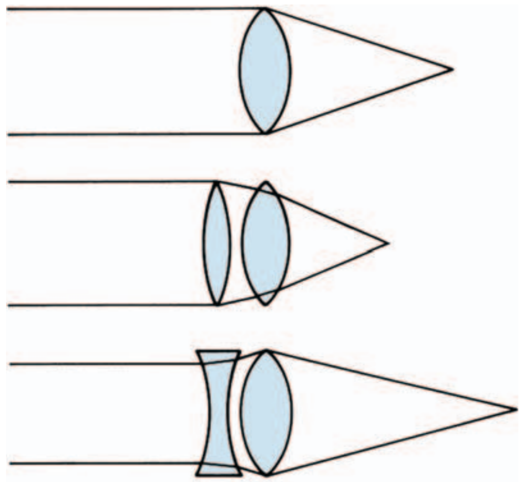


Figure 4-42 The effective local length of a camera lens can be decreased by adding a positive supplementary lens (center), and increased by adding a negative supplementary lens (bottom).

have not yet invaded the large-format camera market.

Supplementary Lenses

Because camera lenses are expensive, photographers sometimes look for less costly alternatives to purchasing additional lenses when their general-purpose lens is not adequate. Supplementary lenses can be used to increase the versatility of a camera lens. Adding a positive supplementary lens produces the equivalent of a shorter focal-length lens, and adding a negative supplementary lens produces the equivalent of a longer focal-length lens. If the supplementary lens is positioned close to the front surface of the camera lens, the focal length of the combination can be computed with reasonable accuracy with the formula $1/f_c = 1/f + 1/f_s$, where f_c is the focal length of the combination, f is the focal length of the camera lens, and f_s is the focal length of the supplementary lens. For example, adding a positive 6-inch supplementary lens to a 2-inch (50-mm) camera lens produces a combined focal length of 1.5 inches (38 mm). Adding a negative 6-inch supplementary lens produces a combined focal length of 3 inches (75 mm) (see Figure 4-42).

If the lenses are separated by a space (d), use the following formula:

$$\frac{1}{f_c} = \frac{1}{f} + \frac{1}{f_s} - \frac{d}{f \times f_s}$$

Supplementary lenses are commonly calibrated in diopters, where the power in diopters equals the reciprocal of the focal length in meters, or $D = 1/f$. To convert from diopters to focal length, use the formula $f = 1/D$. For example, with a 2-diopter lens, $f = 1/2$ meter or 500 mm. With a 4-diopter lens, $f = 1/4$ meter or 250 mm. An advantage of using diopters is that the power of the combination of a camera lens and a supplementary lens is the sum of the individual diopters, or $D_c = D + D_s$.

Adding a positive supplementary lens in effect reduces the focal

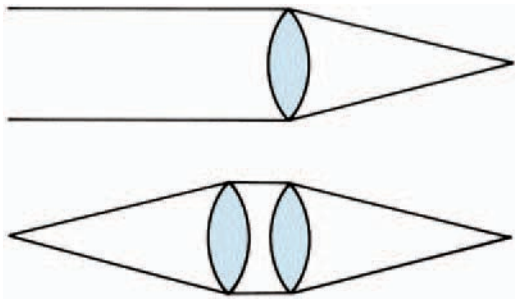


Figure 4-43 Positive supplementary lenses enable cameras to focus on near objects without increasing the lens-to-film distance.

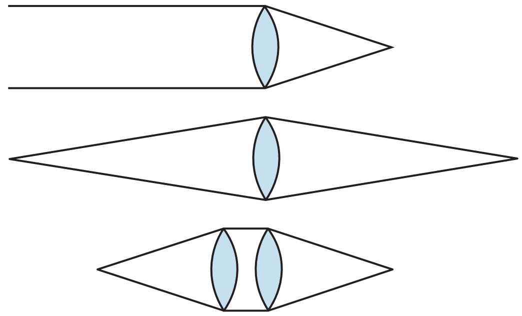


Figure 4-44 Making a 1:1-scale reproduction photograph by increasing the lens-to-film distance (center) requires a 4× increase in the camera exposure. Using a supplementary lens (bottom) requires no increase in exposure.

Adding a positive supplementary lens to a camera lens produces the effect of reducing the focal length of the camera lens.

length of the camera lens, but does not convert it into a wide-angle lens. Therefore, the covering power of the combination may be insufficient to permit use with distant scenes. Keeping the combined lenses at the same distance from the image plane that the camera lens alone would be when focused on infinity will typically provide sufficient covering power. Figure 4-43 illustrates that when a camera is focused on infinity and a positive supplementary lens is added, the point of sharpest focus in object space moves from infinity to a distance of one focal length of the supplementary lens from the camera. Thus, to photograph a small object from a distance of 6 inches, sharp focus would be obtained with a 6-inch focal-length positive supplementary lens on any camera focused on infinity, regardless of the focal length of the camera lens.

When photographing small objects, there can be an advantage in using a supplementary lens rather than increasing the lens-to-film distance with the camera lens alone (when the camera has sufficient focusing latitude). The aberrations in normal-type camera lenses are generally corrected for moderately large object distances, but the corrections do not hold with small object distances and the corresponding large image distances. There is the additional advantage that the camera exposure does not have to be increased when the camera is focused on infinity and a supplementary lens is added. If 1:1-scale reproduction photographs were made with the two procedures, four times the camera exposure would be required using the camera lens alone with the increased lens-to-film distance (see Figure 4-44).

Special Supplementary Lenses

Multiple-element attachments are available to modify the image-forming capabilities of camera lenses. Some of these are not generally referred to as supplementary lenses but rather by terms such as *extender (or converter)*, *afocal attachment*, and *monocular attachment*.

Extenders are negative lenses containing one or more elements that are used behind the camera lens to increase the focal length. They are commonly referred to as tele-extenders, as they are most effective when used with telephoto or other longer-than-normal focal length lenses and produce a telephoto effect with the addition of a negative lens behind the positive camera

lens. A tele-extender will increase the focal length of whatever camera lens it is used with by the same factor, such as 2×, although some are variable to produce different factors.

Afocal attachments combine positive and negative elements having appropriate focal lengths and separation between them so that rays of light entering the attachment from a distant object point leave traveling parallel, as in a Galilean telescope. Since the attachment does not form a real image, it has no focal length, hence the name afocal. Afocal attachments do alter the focal length of the camera lens, however, increasing it when the positive component is in front of the negative component, and decreasing it when the negative component is in front of the positive component, as illustrated in Figure 4-45. With the camera lens focused on infinity and the afocal attachment added, focus can be adjusted for different object distances by changing the distance between the positive and negative elements. Changing the ratio of the focal lengths of the positive and negative elements alters the effect of the attachment on the focal length of the combination and, therefore, image size. The afocal attachment has no effect on the *f*-number of the camera lens.

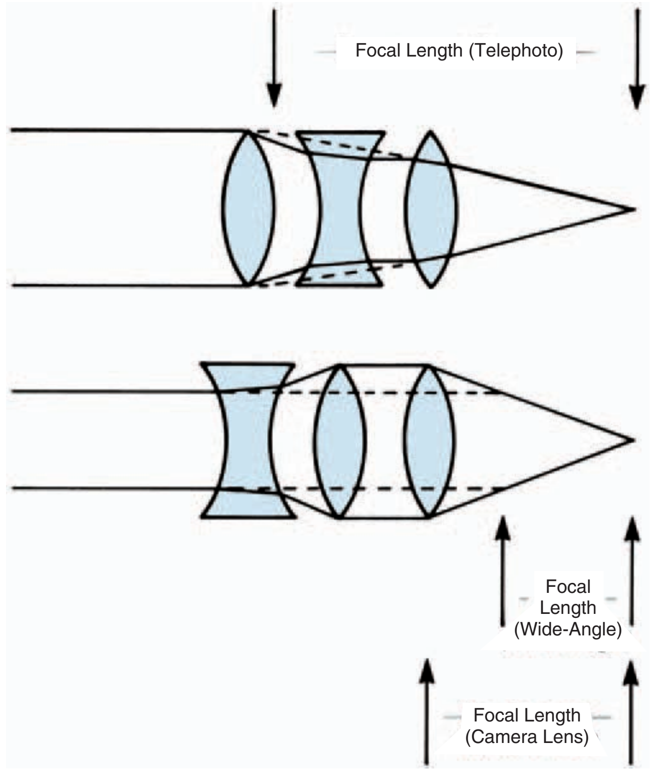


Figure 4-45 Afocal attachments change the effective focal length of camera lenses without changing the lens-to-film distance or the *f*-number. A two-element telephoto attachment is shown in front of a camera lens, at the top; a wide-angle attachment is shown at the bottom.

Convertible Lenses

Convertible lenses are designed so that one or more elements can be removed to change the focal length. Removing a positive element or group of elements increases the focal length. Removing the part of a compound lens that is in front of or behind the diaphragm introduces other complications. Since the focal length and the lens-to-film distance are both increased with the removal of a positive component, the *f*-numbers will be affected and a separate set of markings must be provided. This differs from the addition of an afocal attachment, where the focal length is altered but the camera lens-to-film distance and therefore the *f*-numbers are unaffected.

Although multiple elements can be used in both components of a convertible lens to minimize aberrations, the photographer should not expect the same image quality when part of the lens is removed. If a component is removed from a convertible lens to obtain a longer focal length for the purpose of making portraits, for example, the loss of image sharpness at large diaphragm openings may be flattering rather than detrimental, and stopping the lens down will reduce any loss of sharpness. Disrupting the

Two different focal lengths can be obtained with convertible lenses by removing part of the lens.

symmetry of the lens on both sides of the diaphragm by the removal of one component without introducing barrel or pincushion distortion presents the lens designer with a difficult problem.

A more recent variation of the convertible lens is the substitution of a different component. This procedure makes it possible to maintain a higher degree of aberration correction and to offer a greater variety of longer and shorter focal lengths at a lower price than for completely separate lenses with different focal lengths.

Zoom Lenses

From the photographer's point of view, the ideal solution to the problem of having the right lens available for every picture-making situation is to have one versatile variable focal-length lens. Lens designers have made excellent progress toward the goal of a universal lens with the zoom design. With a zoom lens, the focal length can be altered continuously between limits while the image remains in focus. The basic principle involved in changing the focal length of a lens can be illustrated with a simple telephoto lens where the distance between the positive and negative elements is varied, as illustrated in Figure 4-46. This change in position of the negative element would change the focal length (and image size and angle of view), but the image would not remain in focus. Other problems include aberration correction and keeping the relative aperture constant at all focal length settings. It should not be surprising that one of the early zoom lenses contained more than twenty elements, was large and expensive, and was not very successful in solving all of the basic problems. Better zoom lenses are now being mass produced with relatively few elements, because of design improvements.

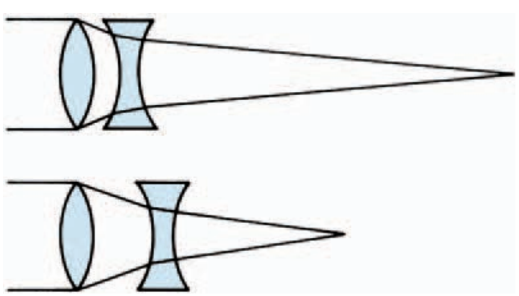


Figure 4-46 Changing the distance between the positive and negative elements of a telephoto lens changes the focal length.

Two methods have been used for the movement of elements in zoom lenses. One is to link the moveable elements in the lens so that they move the same distance. This is called *optical compensation* because the mechanical movement is simple, but the optical design is complex and requires more elements. The other method is called *mechanical compensation* and involves moving different elements by different amounts, requiring a complex mechanical design. For the problem of maintaining a constant *f*-number as the focal length is changed, an *optical solution* is to incorporate the concept of the afocal attachment at or near the front of the lens so that the aperture diameter and the distance between the diaphragm and the film can remain fixed. An alternative mechanical solution is to use a cam that adjusts the size of the diaphragm opening as the focal length is changed.

There are also mechanical and optical methods for keeping the image in focus. The mechanical method consists of changing the lens-to-film distance, as with conventional lenses. The optical method involves using a positive element in front of the afocal component that is used to keep the relative aperture constant. The range of maximum-to-minimum focal length varies with different zoom lenses from less than 3:1 to

more than 20:1, with the larger ranges found only on lenses for motion-picture and television cameras.

Digital Zoom

The zoom lenses we have discussed thus far are optical zoom lenses, meaning the position of individual lens elements or combinations of lens elements within the zoom lens are changed to enlarge the image captured on the image plane. However, many amateur digital cameras enlarge the image through the use of digital zoom.

Digital zoom functions by cropping the digital sensor in the camera when capturing the image. The data is then interpolated or "enlarged" back to the full resolution of the digital sensor. Using digital zoom, just as optical zoom, also decreases the angle of view of the digital image. This process is meant to simulate optical zoom. Often during this process image definition is lost.

If the camera saves the digital image in RAW format, using the digital zoom on the camera will produce the same result as capturing the image and then enlarging it with image editing software later. However if the camera saves the image using a lossy image compression, such as JPEG, digital cropping may give a superior result over manual cropping later. This can happen because the on-board software may perform the interpolation prior to saving the image.

Macro-Zoom Lenses

Zoom lenses generally were not made to focus on short object distances. In 1967, the first of a series of macro-zoom lenses was introduced. Macro-zoom lenses are designed to photograph small objects near the camera either by extending the conventional focusing range or by making a separate adjustment in the position of certain components for the so-called macro capability. Use of the term *macro* in this context is misleading, as most lenses of this type produce a maximum scale of reproduction no larger than 1:2. To date, none yields a scale larger than 1:1, which is considered the lower limit for the specialized area of photography called photomacrography.

Use of digital zoom will often result in the loss of image definition.

Macro Lenses

Normal-designed lenses that produce excellent quality images with objects at moderate to large distances may not perform well when used at small object distances. At scales of reproduction larger than 1:1, where the image distance is greater than the object distance, such lenses tend to produce sharper images when they are turned around so that the front of the lens faces the film. Macro lenses are small-format camera lenses especially designed to be used at small object distances. The important optical characteristic of macro lenses is the excellent image definition they produce under these conditions compared with normal-type lenses (see Figure 4-47). The lens designer's task of optimizing aberration correction for small object distances is made easier by removing the additional requirement to make the lens fast. Thus most macro lenses are two or three stops slower than comparable normal-type lenses. The implication that macro lenses are not suitable for photographing objects at larger distances is not entirely valid, however. Because of the slower maximum speed, the aberration corrections are not as sensitive to changes in object distance, and some photographers prefer to use a macro lens for general-purpose photography when a faster lens is not needed.

A zoom lens should keep the image in focus and keep the image illuminance constant as the focal length is altered.

Macro lenses are designed to produce better image definition than conventional lenses when used at small object distances.

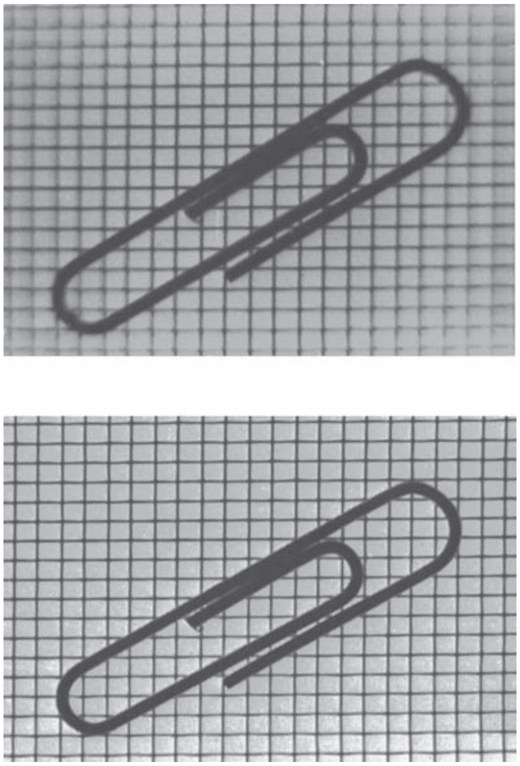


Figure 4-47 Photographs of a small object made with a normal-type camera lens (top) and a macro lens (bottom), both at the maximum aperture.

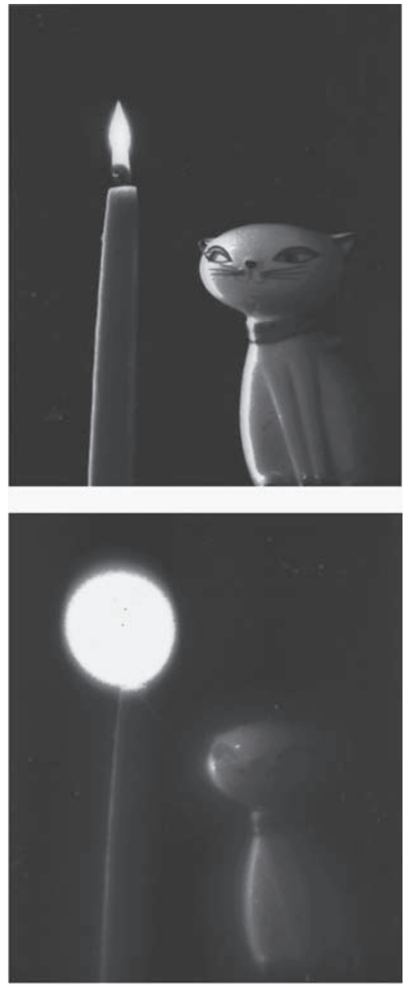


Figure 4-48 Photographs made with a normal-type camera lens (top) and a single-element lens that was uncorrected for spherical aberration (bottom).

Spherical aberration is commonly used to produce the soft focus with soft-focus lenses.

Soft-Focus Lenses

Photographers typically want a lens to produce sharp images, but for some purposes a certain amount of unsharpness is considered more appropriate. *Soft-focus* lenses are sometimes labeled portrait lenses because they have been used so widely for studio portraits. However, soft-focus lenses have also been used extensively by other photographers, including pictorialists and even photographers doing advertising illustration, when certain mood effects are desired.

The soft-focus effect is generally achieved by undercorrecting for spherical aberration in designing the lens. Since spherical aberration is reduced as the lens is stopped down, the photographer can control the degree of unsharpness by the choice of *f*-number. To the discerning viewer, the effect produced with a soft-focus lens on the camera is not at all similar to that produced by defocusing the enlarger or diffusing the image while exposing the print with a sharp negative. Rays of light near the axis of a soft-focus lens form a sharp image, which is surrounded by an unsharp image formed by the marginal rays of light so that highlight areas in the photograph appear to be surrounded by halos (see Figure 4-48). If the same lens were used on an enlarger, the shadows in prints would be surrounded by dark out-of-focus images, except when making reversal prints from transparencies.

Anamorphic Lenses

An anamorphic lens produces images having different scales of reproduction in each of two perpendicular directions, usually the vertical and horizontal directions. It is common practice to think of one of the two dimensions of the image as being normal and the other as being either stretched or squeezed. Even before photography, some artists were experimenting with anamorphic drawings where, for example, it was necessary to view the image at an extreme angle for it to appear normal. Lens designers have long been familiar with the concept of anamorphic lenses, but there was little demand for such lenses before the introduction of wide-screen motion pictures.

Motion-picture cameras equipped with anamorphic lenses have a wider-than-normal horizontal angle of view, but the extra width is squeezed by the lens to fit the conventional film format, which typically has an aspect ratio of 1.33:1. The projector, in turn, is equipped with an anamorphic lens that will stretch or unsqueeze the horizontal dimension to produce a picture with a higher aspect ratio (1.8:1, for example) and images that appear normal (see Figure 4-49).

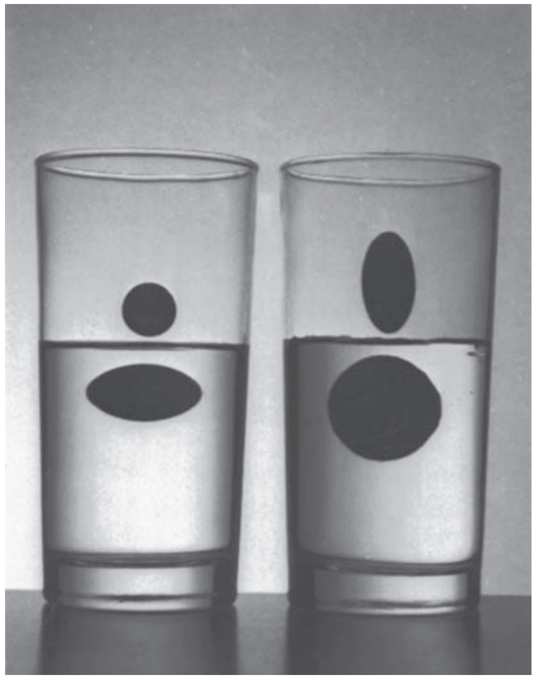


Figure 4-49 The water-filled parts of the glasses function as anamorphic lenses to stretch the images horizontally. Two stretched images of the penny on the left were rotated 90° and placed on the glass on the right where the bottom one was stretched back to a circular shape by the water. With wide-screen cinematic photography, the anamorphic camera lens squeezes a wide angle of the scene onto normal-width film, and the anamorphic projector lens stretches or unsqueezes the image to fit a wide projection screen.

Motion picture anamorphic camera lenses squeeze a wide angle of the scene onto standard-width film. The projector anamorphic lens unsqueezes the film image onto a wide projection screen.

Enlarger Lenses

The requirements for enlarger lenses are similar to those for a camera lens intended for copying, with aberrations minimized for small object distances, and in practice, the degree of correction can be expected to vary with the price for a given focal length. In the past, most enlarging lenses were designed for normal covering power with the expectation that the photographer would select a focal length about equal to the diagonal of the film format. Recent years have seen the increasing use of shorter focal-length lenses with larger angles of coverage to increase the range of scales of reproduction, and the range of image sizes that can be obtained with a given enlarger at the upper and lower limits of elevation.

The introduction of variable focal-length enlarger lenses followed years behind widespread use of variable focal-length lenses for motion-picture cameras, television cameras, small-format still cameras, and slide projectors.

Four types of lens shortcomings are related to (1) image definition, (2) image shape, (3) image illuminance, and (4) image color.

Lens Shortcomings

The geometrical drawings used to illustrate image formation in preceding sections imply that the lenses form perfect images. This is not the case,

The diffraction-limited resolving power of a lens can be calculated by dividing a constant by the *f*-number.

Practical lens tests done by examining photographs made with the lens are systems tests rather than lens tests.

of course. Actually, there is no need for such perfect images in the field of pictorial photography, where photographs tend to be viewed from a distance about equal to the diagonal, and, as noted earlier, circles of confusion up to a certain maximum size are perceived as points. This tolerant attitude does not apply to photographs viewed through magnifiers or microscopes to extract as much information as possible, or even pictorial photographs that are enlarged and cropped in printing. Lens shortcomings can be subdivided into four categories: those that affect image definition, image shape, image illuminance, and image color.

Diffraction

Diffraction is the only lens aberration that affects the definition of images formed with a pinhole. According to the principles of geometrical optics, which ignore the wave nature of light, image definition will increase indefinitely as a pinhole is made smaller. In practice there is an optimum size, and image definition decreases due to diffraction as the pinhole is made smaller. The narrow beam of light passing through the pinhole from an object point spreads out in somewhat the same manner as water coming out of a nozzle on a hose, and the smaller the pinhole the more apparent the effect.

Similarly, the definition of an image formed by an otherwise perfect lens would be limited by diffraction. Some lenses are referred to as *diffraction-limited* because under the specified conditions they are that good. Using resolution as a measure of image definition, the diffraction-limited resolving power can be approximated with the formula $R = 1{,}800/N$, where R is the resolving power in lines per millimeter, 1,800 is a constant for an average wavelength of light of 550 nm, and N is the *f*-number. Thus a lens having minimum and maximum *f*-numbers of $f/2$ and $f/22$ would have corresponding diffraction-limited resolving powers of 900 and 82 lines/mm. If the resolution is to be based on points rather than lines, the formula is changed to $R = 1{,}500/N$ (see Table 4-2).

Lens Testing

Photographers who inquire about testing a lens are commonly advised to do so by making photographs of the same type that they expect to be making with the lens in the future, and to leave the more analytical testing to lens designers, manufacturers, and others who have the training and the sophisticated equipment necessary for the job. It makes sense that a photographer should not worry about shortcomings in the imaging capabilities of a lens if the effects are not apparent in photographs made with the lens. On the other hand, many photographers use their normal lens in a variety of picture-making situations, and certain lens shortcomings may appear in one photograph and not in another. Thus, the subject matter and the conditions for even a practical test of this type must be carefully controlled.

To test for image definition, the following are required:

1. The subject must conform to a flat surface that is perpendicular to the lens axis and parallel to the image plane.
2. The subject must exhibit good detail with local contrast as high as is likely to be encountered, not of a single hue such as red bricks or green grass.
3. The subject must be large enough to cover the angle of view of the camera-lens combination at an average object distance.

Table 4-2 Diffraction-limited resolving power vs. *f*-numbers. (The underlined rows identify the *f*-numbers that would produce the same diffraction-limited resolving power of 14 lines/mm on 8 × 10-inch prints made from five different size negatives)

F-Number	l/mm	Film size	Adjusted for 8 × 10 Print
$R = \frac{1800}{F - number}$			
f/1	1800		
f/1.4	1286		
f/24	900		
f/2.8	643		
f/4	450		
f/5.6	321		
f/8	225		
f/11	160		
f/16	112	1–1½	112/8 = 14
f/22	80		
f/32	56	2¼	56/4 = 14
f/45	40		
f/64	28	4 × 5	28/2 = 14
f/90	20		
f/128	14	8 × 10	14/1 = 14
f/180	10		
f/256	7	16 × 20	7/0.5 = 14
f/360	5		

Note: 1,500 used for points; 1,800 for lines.

$$R = \frac{10^6}{\lambda \times f - number} \text{ where } \lambda = 550\,\text{nm}$$

4. The subject must also be photographed at the closest object distance likely to be used in the future.
5. Photographs must be made at the maximum, minimum, and at least one intermediate diaphragm opening.
6. Care must be taken to be certain that the optimum image focus is at the film plane, which may require bracketing the focus.
7. Care must be taken to avoid camera movement, noting that mirror action in single-lens reflex cameras can cause blurring of the image, especially with small object distances or long focal length lenses. Outdoors, wind can cause camera movement.

If the same subject is to be used to test for image shape, it must have straight parallel lines that will be imaged near the edges of the film or sensor to reveal pincushion or barrel distortion (see Figure 4-50). If it is also to be used to test for uniformity of illumination at the image plane, it must contain areas of uniform luminance from center to edge. Tests for flare and ghost images require other subject attributes. We

Figure 4-50 Simulates barrel distortion image. Note that the distortion does not affect radial subject lines—straight subject lines that intersect the lens axis, such as the horizon line and the center vertical line. (Photograph by Brandyn Balch, Photojournalism student, Rochester Institute of Technology.)

can conclude that a practical test cannot be overly simple if it is to provide much information about the lens. In any event, evaluation of the results is easier and more meaningful if a parallel test is done on a lens of known quality for comparison.

Practical tests such as these are not really lens tests, but rather they are systems tests, which include subject, lens, camera, film, exposure, development, the enlarger, and various printing factors. In the case of a digital camera system, test factors examined would be the subject, lens, camera, digital sensor, on-board processing, and whatever output device would be used, such as a monitor, ink jet or laser printer. The advantage that such tests have of being realistic must be weighed against the disadvantage that tests of a system reduce the effect of variations of one component, such as the lens, even if all the other factors remain exactly the same. For example, if two lenses having resolving powers of 200 and 100 lines/mm are used with a film having a resolving power of 100 lines/mm, the resolving powers of the lens-film combinations would be 67 and 50, using the formula $1/R = 1/R_L + 1/R_F$. Thus, only dramatic differences between lenses will be detected easily in the photographs.

The influence of other factors in the system can be eliminated by examining the optical image directly, either on a finely textured ground glass or by removing the ground glass and examining the aerial image. A good-quality magnifier or low-power microscope should be used. An artificial star, made by placing a lightbulb behind a small hole in thin, opaque material, is commonly used to check image definition by noting how the image deviates from an ideal point image. Since the ideal is seldom approximated closely, it is better to evaluate a lens by comparison with a lens of known quality than by judging it alone. By placing the artificial star at an appropriate distance on the lens axis, the effect of stopping down on spherical and longitudinal chromatic aberrations can be seen. The chromatic aberration can be removed by placing a green filter behind the hole to study spherical aberration alone. Moving the star laterally so that the image appears near a corner will reveal off-axis defects, including coma and lateral chromatic aberration.

Resolving power has been a widely used but controversial method of checking image definition. The testing procedure is simple. The lens is focused on a row of resolution targets that contain alternating light and dark stripes and that are placed at a specified distance from the lens (see Figure 4-51). The separate targets are arranged so that the images fall on a diagonal line on the ground glass or film plane with the center target on the lens axis, and oriented

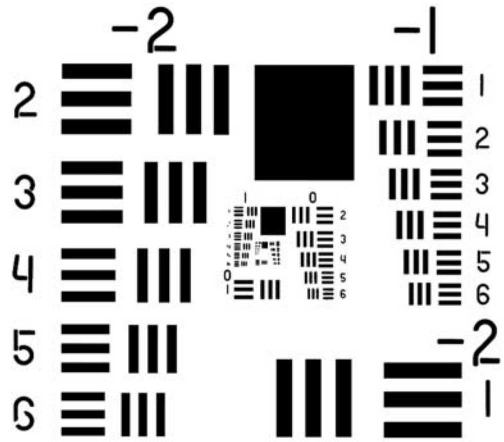


Figure 4-51 USAF Resolving-power target.

so that the mutually perpendicular sets of stripes constitute radial and tangential lines. The aerial images are examined through a magnifier or microscope of appropriate power, and the smallest set of stripes that can be seen as separate "lines" is noted for each target. Resolving power is the maximum number of light-dark line pairs per millimeter that can be resolved.

Critics of resolving power note that different observers may not agree on which is the smallest set of stripes that can be resolved, and that in comparing two lenses, photographs made with the lens having the higher resolving power sometimes appear to be less sharp. In defense of resolving power, it has been found that observers can be quite consistent even if they don't agree with other observers. Consistency makes their judgments valid on a comparative basis such as between on-axis and off-axis images, images at two different *f*-numbers, and images formed with two different lenses. It is appropriate to make comparisons between lenses on the basis of resolving power as long as it is understood that resolving power relates to the ability of the lens to image fine detail rather than the overall quality of the image.

Electronic methods have largely replaced visual methods of testing lenses in industry. The equipment required is complex and expensive but it is capable of providing comprehensive and objective data quickly. The results are commonly presented in the form of modulation-transfer-function curves in which the input spatial frequency is plotted as cycles per millimeter on the horizontal axis against output contrast as percent modulation on the vertical axis. Representative curves for three different lenses, two having imaging shortcomings, are shown in Figure 4-52, where lens B has higher contrast in the high-frequency (fine detail) areas but lower contrast in the low-frequency (coarse detail) areas than lens C. The accompanying pictures illustrate that a photograph in which fine detail is better resolved may appear less sharp because of the lower contrast in the larger image areas.

Resolving power is not a reliable indicator of the appearance of sharpness of photographic images.

Testing Flare

Optical images formed with lenses are always less contrasty than the scenes being photographed because of the effects of flare light. Antireflection lens coatings are effective in reducing the proportion of light reflected from lens surfaces and increasing the proportion of light, transmitted, but they only reduce flare light, not eliminate it. In practice, flare light that falls on film or the sensor in a camera is a combination of lens flare and camera flare, and the amount of flare light can vary greatly with a given lens, depending upon the distribution of light and dark tones in the scene, the lighting, the interior design of the camera, and whether or not a lens shade is used. Thus, flare tests can be conducted with the lens in a laboratory where a standard test target is used and the effects of the camera are eliminated, or they can be conducted with the lens on a camera

Camera flare light reduces the contrast of photographic images, especially in shadow areas.

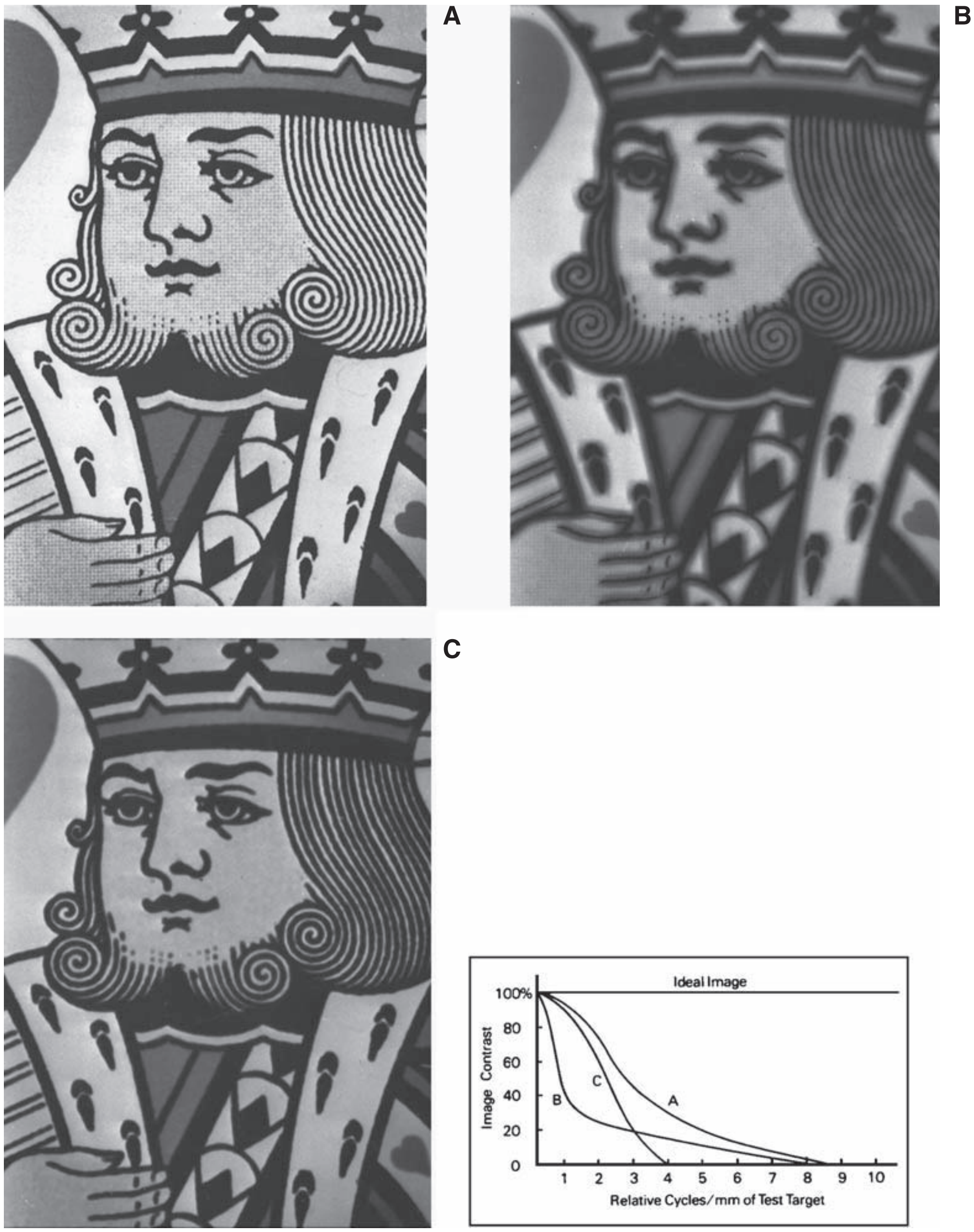


Figure 4-52 Prints made from a copy negative with three different lenses, and representative modulation transfer function curves. Lens A was a high-quality enlarging lens. The lens B image shows a large loss of contrast in the intermediate frequencies, while the lens C image shows the largest loss in the high frequencies. Lens B would score higher on a resolving-power test even though photographs made with lens C tend to appear sharper because of the higher contrast of the intermediate-size tonal areas.

with a representative scene or a variety of scenes.

Flare light can be specified in various ways—as a flare factor, as a percentage of the maximum image illuminance, and graphically as a flare curve. The flare factor is defined as the scene luminance ratio divided by the image illuminance ratio. The flare factor can most easily be determined with a large-format camera and an in-camera meter of the type where a probe can be positioned to take readings in selected small areas such as a

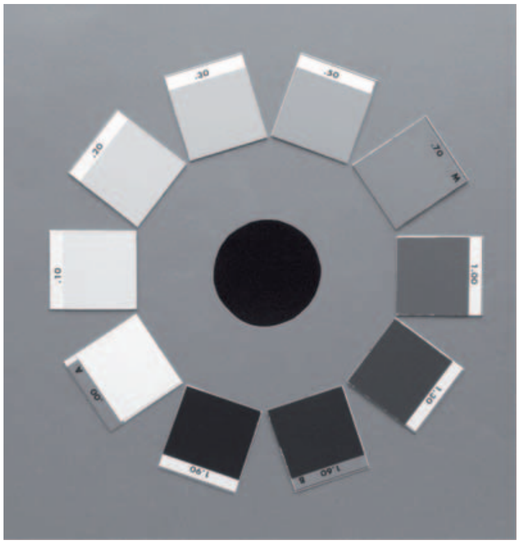


Figure 4-53 A black hole in a neutral test card surrounded by a gray scale, used to determine the flare factor in a given situation.

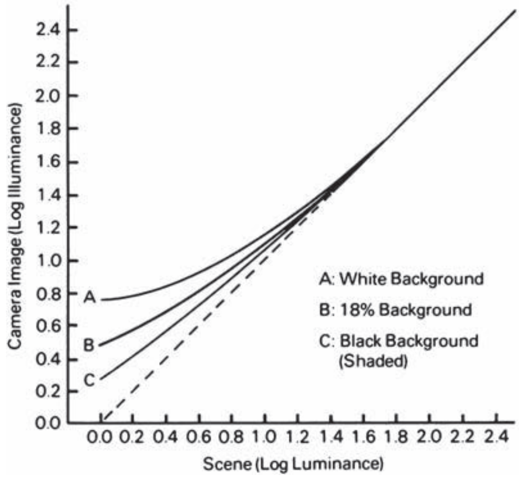


Figure 4-54 Flare curves prepared by taking meter readings at the film plane of the image of a gray scale with white, gray, and black backgrounds. The straight broken line represents the complete absence of flare light.

highlight and a shadow. If the image illuminance ratio is 80:1 with a scene having a luminance ratio of 160:1, the flare factor is 160/80 = 2. Flare factors are typically between 2 and 3, but they can be much higher.

An opaque black card placed in front of a large transparency illuminator in an otherwise darkened room can be used to determine the percentage of flare light by dividing an illuminance reading of the image of the black card by an illuminance reading of the image of the transparency illuminator. A white surface and a black hole can be placed in any scene and used in the same way, where the black hole is a small opening in an otherwise light-tight enclosure painted black on the inside (see Figure 4-53). Standard test targets and simple procedures are available for the routine determination of the percentage of flare with process cameras in the graphic arts field where flare levels above 1.5% are considered excessive. With a normal scene having a luminance ratio of 160:1, a flare level of 1.5% corresponds to a flare factor of 2.4.

Flare curves can be prepared in various ways. One method is to place a step tablet or gray scale, with an appropriate surround, in front of a large-format camera, measure the relative illuminance of each step of the image with an in-camera meter, and plot log relative illuminance on the vertical axis vs. log relative luminance (that is, 1/density) of the original on the horizontal axis (see Figure 4-54).

Lens hoods help reduce flare.

REVIEW QUESTIONS

1. If a pinhole aperture is used on a view camera in place of the lens, increasing the pinhole-to-ground-glass distance results in . . .

   A. an increase in the image size

   B. a decrease in the image size

   C. no change in the image size

2. Diffraction causes the greatest degradation of the pinhole image when . . .

   A. the pinhole-to-ground-glass distance is less than the film diagonal

   B. the pinhole-to-ground-glass distance is larger than the film diagonal

C. the pinhole is too large
D. the pinhole is too small

3. Anamorphic pinhole images can be obtained by using . . .

A. two pinholes, side by side
B. a rectangular pinhole aperture
C. crossed slits at different distances from the film
D. anamorphic film

4. The focal length of a lens is the distance from the . . .

A. film to the lens
B. principal focal point to the back nodal point
C. front nodal point to the back nodal point
D. subject to the lens

5. The image distance that produces an in-focus image for an object located 300 mm from a 200-mm lens is . . .

A. 200 mm
B. 300 mm
C. 400 mm
D. 600 mm
E. 800 mm

6. Image size is . . .

A. directly proportional to focal length
B. directly proportional to focal length squared
C. inversely proportional to focal length
D. inversely proportional to focal length squared

7. Two objects of equal size are located at distances of 10 feet and 20 feet from a camera. If the image of the nearer object measures 1 inch in the photograph, the image of the farther object will measure . . .

A. 1/4 inch
B. 1/2 inch
C. 1 inch
D. 2 inches
E. 4 inches

8. When a camera is moved farther away from a subject, the perspective . . .

A. becomes stronger
B. becomes weaker
C. is unchanged

9. The image of a distant building formed with a 90-mm focal length lens on a 4 × 5-inch view camera is 1-inch tall. To obtain an image that is 3 inches tall with the camera in the same position, it would be necessary to substitute a lens with a focal length of . . .

A. 30 mm
B. 60 mm
C. 135 mm
D. 180 mm
E. 270 mm

10. The recommended procedure for selecting the lens and the camera position for a photograph when perspective is an important factor is to select the . . .

A. lens first, then the camera position
B. camera position first, then the lens

11. The "correct" viewing distance for an 8 × 10-inch print made from a 35-mm negative exposed with a 50-mm focal-length lens is approximately . . .

A. 50 mm
B. 8 inches
C. 10 inches
D. 12.8 inches
E. 16 inches

12. The heads near the left and right edges of a group portrait appear to be abnormally broad. This unnatural shape is associated with . . .

A. barrel distortion
B. pincushion distortion
C. curvature of field
D. the wide-angle effect
E. the balloon effect

13. The largest circle that will appear as a point on a print viewed at the standardized viewing distance is generally considered to have a diameter of approximately . . .

A. 1/50 inch
B. 1/100 inch
C. 1/200 inch
D. 1/400 inch
E. 1/800 inch

14. A definition of hyperfocal distance is . . .

A. the nearest distance that appears sharp when the camera is focused on infinity

B. the distance from the lens to the film when the camera is focused on infinity
C. one-half the distance to infinity when the lens is one focal length from the film
D. the distance between the nearest and farthest objects that appear sharp

15. A lens has a maximum aperture of *f*/2.0 and a minimum aperture of *f*/16. At *f*/16, the depth of field (DOF) will be . . .

A. 4 times the DOF at *f*/2
B. 8 times the DOF at *f*/2
C. 16 times the DOF at *f*/2
D. 32 times the DOF at *f*/2
E. 64 times the DOF at *f*/2

16. The object distance at which the largest depth of field is obtained for a given lens and *f*-number is . . .

A. infinity
B. 1/2 the hyperfocal distance
C. the hyperfocal distance
D. 2 times the hyperfocal distance

17. Two photographs are made with a 4 × 5-inch camera, the first with a 200 mm focal-length lens and the second with a 400 mm focal-length lens. If both photographs are made at the same *f*-number and with the camera in the same position, the depth of field in the first photograph will be . . .

A. 2 times that in the second
B. 4 times that in the second
C. 8 times that in the second
D. the same as that in the second

18. Image shape is controlled by tilting or swinging . . .

A. the lens (only)
B. the back (only)
C. either the lens or the back

19. To control both shape and sharpness of the image of an object, the photographer should control . . .

A. sharpness with the back and shape with the lens
B. sharpness with the lens and shape with the back
C. both sharpness and shape with the back
D. both sharpness and shape with the lens
E. none of the above

20. The plane of sharp focus is controlled by tilting or swinging . . .

A. the lens (only)
B. the back (only)
C. either the lens or the back

21. A 50-mm focal length lens produces a 1/2 mm diameter image of a full moon. To obtain an image with a diameter of 24 mm to completely fill the width of a 35-mm negative would require a lens having a focal length of . . .

A. 240 mm
B. 480 mm
C. 2400 mm
D. 4800 mm
E. Insufficient information provided

22. A simple telephoto lens consists of . . .

A. a positive element in front of and separated from a negative element
B. a negative element in front of and separated from a positive element
C. a positive element and a negative element with an adjustable space between them
D. none of the above

23. A valid reason for using a 90-mm focal-length wide-angle lens in preference to a 210-mm focal length lens of normal design on a view camera would be to obtain . . .

A. a larger angle of view
B. a smaller angle of view
C. a shallower depth of field
D. a larger circle of good definition

24. A problem that would be encountered in using a 28-mm focal-length wide-angle lens of conventional design on a 35-mm SLR camera is inability to . . .

A. focus on infinity
B. focus close up
C. use the focal plane shutter
D. use the reflex viewfinder
E. stop the lens down beyond *f*/8

25. Adding a +12-inch focal length supplementary lens to a 6-inch focal-length camera lens produces

a combined focal length of approximately . . .

A. 2 inches
B. 3 inches
C. 4 inches
D. 9 inches
E. none of the above

26. A 35-mm camera that is equipped with a 50-mm focal-length lens is focused on infinity. A 50-mm positive supplementary lens is added to the camera lens. The camera is now in sharp focus for an object distance of . . .

A. 35 mm
B. 50 mm
C. 100 mm
D. none of the above

27. An advantage of a macro lens over a lens of normal design of the same focal length is . . .

A. lower cost
B. larger depth of field
C. higher speed (smaller *f*-number)
D. better definition with small object distances

28. The only aberration that affects images formed with pinhole apertures is . . .

A. spherical aberration
B. diffraction
C. coma
D. curvature of field
E. distortion

29. The diffraction-limited resolving power for a 50-mm focal length lens on a 35-mm camera, at a diaphragm opening of *f*/2, is . . .

A. 1,800 lines/mm
B. 900 lines/mm
C. 450 lines/mm
D. 225 lines/mm

30. In lens testing, resolving power is associated with . . .

A. graininess
B. sharpness
C. detail
D. overall quality

chapter

5

Sensitometry

Photograph by Elliot Krasnopoler, Advertising Photography student, Rochester Institute of Technology

Introduction

Prior to the introduction of digital cameras, *sensitometry* was defined as the scientific evaluation of the response of a photographic emulsion to light. Today, sensitometry would better be defined as the scientific evaluation of a light-sensitive material to light. While there are some similar concepts between a digital system and photographic film sensitometric study, there are also many differences. The basic steps in a photographic film sensitometric study would be expose and develop the film, measure the densities, plot the data and analyze. The same process applies to doing a sensitometric study of photographic papers. For a digital sensitometric study, the process is to capture an image, determine the digital counts, plot the data and analyze, or instead of plotting data, the digital data can be analyzed using software.

Sensitometry provides quantitative information about light-sensitive materials. For a digital still camera (DSC), that would include such things as an ISO speed rating, recommended exposure index, and the standard output sensitivity. In a classic film-based system, these measurements would include an ISO speed rating, gamma value, contrast index, and exposure index.

Sensitometry can be further broken down into two main categories: camera and print. We will discuss the camera first for both digital and film systems. Prior to printing, photographers should have a complete understanding of how the image

sensor or the film is performing. Once there is a complete understanding of the sensor or film, then a study of prints can take place.

Exposure

The exposure in both systems must be done in a controlled manner so that the input luminances are known. That is, we must be able to know what the subject input is. Several approaches can be used here.

The first approach would be to measure many different tones in an input scene. Areas of low lightness or reflectance would be shadow tones, while areas with high lightness are highlight tones. These reflected light values are luminances and are a measure of intensity of light per unit area. The basic unit of measurement is the *candela per square foot*.

Most photoelectric meters are equipped to measure the subject luminances by using the meter in the reflected light mode and pointing it at the area to be measured. The readings are usually in the form of arbitrary units that are proportional to the luminance in candelas per square foot.

An alternative method for obtaining input data about the subject is to use a reflection gray scale as a standardized reference. A gray scale is an organized set of subject tones displayed with known tonal values. These tonal values have been pre-measured on a reflection densitometer, and the values shown are reflection densities. Figure 5-1 shows two grayscales. Figure 5-1(A) is commonly used for film studies and is inexpensive. Although it can also be used for digital cameras, the ISO has created a similar, more expensive target for use with digital cameras (see Figure 5-1(B)).

Most gray scales have a total luminance ratio of approximately 100:1 and are therefore close to representing an average outdoor scene that usually has a 160:1 luminance ratio. (A luminance ratio is the ratio of the brightest area in scene to the darkest area in the scene.) As input data, the only significant difference between grayscale data and subject log luminance values are that the numbers run opposite to each other. This is because reflection density is a measure of the amount of darkening occurring in an image, while luminance is a measure of the amount of light emanating from a surface. Therefore, the two concepts are reciprocally related. Although the concept of density will be addressed in detail later, it is important to note that the reflection densities of the gray scale are themselves logarithms, since, by definition, reflection density is the logarithm of the reciprocal of the reflectance.

When analyzing a digital system the accepted method for obtaining input data is to use the ISO 14524 target. The ISO has established a standard (ISO 12232) that outlines the required

A

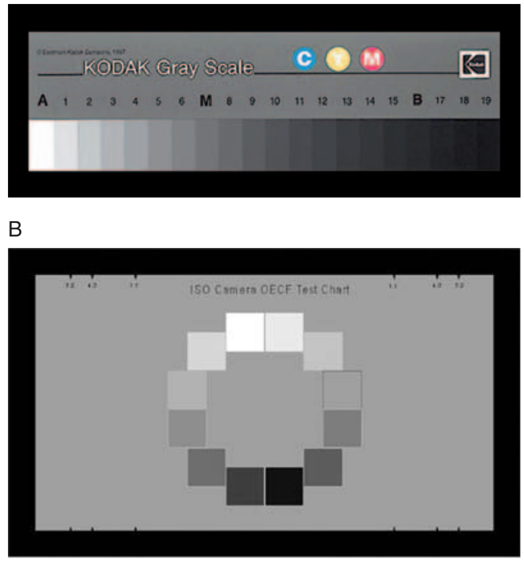


Figure 5-1 (A) Grayscale that can be used in tone reproduction studies. (B) ISO-14524 12-patch OECF target for use with digital cameras.

method for making an exposure when the resulting data will be used in a sensitometric study. The illumination should be either CIE illuminant D_{55} or tungsten illumination having a color temperature of 3,050 K. The ambient temperature of the area where the exposure is made should be $(23 \pm 2)°$ C with a relative humidity of $(50 \pm 20)\%$. The camera white balance should be adjusted so that the signal levels for the RGB are equal. That is, when the exposure is made, the white patch in the target should have equal values for the red, green, and blue digital counts. The IR blocking filter should be in place. In most cameras, this cannot be removed. The shutter speed shall not exceed 1/30 second. If possible, no compression will be done to the image prior to saving it on the camera memory card. All other camera setting options should be set to the manufacturer's default settings. Finally, when making the exposure, the digital count values for the lightest patch on the target shall be as close to the maximum digital count available for the camera without clipping occurring.

For film, however, there is another option. Although cameras are the principal instruments used to expose film in practice, they are not the best choice for film testing purposes. The goal is for the film to receive a set of known exposures. The known illuminances and times are then used to calculate the exposures the film received. Because of light falloff and flare problems at the image plane, it is difficult to calculate accurate illuminance values from the subject luminances and the *f*-number. Additionally, the shutter speeds marked on most cameras may not correlate closely with the actual exposure times. Unless the shutter has been pre-tested and found to be consistent and accurate, reliable information about the exposure time will not be obtained. Devices specifically designed to expose film for testing purposes are called sensitometers.

A sensitometer consists of three major parts as shown in Figure 5-2: a light source, a step tablet, and a shutter. Sensitometers and cameras are both used to expose film. A sensitometer, however, has its own light source and subject (step tablet). Because a sensitometer is not a camera and is not a direct part of the picture-making process, great care is taken so it simulates actual picture-making conditions. For example, the light source is chosen so the color it produces matches that used in reality. Since the most commonly encountered light is daylight, sensitometric light sources that approximate its color quality are used. Usually, a tungsten lamp with appropriate filtration is used because it can be precisely calibrated and is very stable over its lifetime. Some sensitometers make use of a xenon-filled flashtube (electronic flash) source, which does not require filtration since its spectral output already is close to the color of daylight. Whatever source is used, the illumination reaching the film plane is nearly uniform and can be measured easily.

Clipping is when a highlight region of a scene records at the largest pixel value available or a shadow region at the lowest pixel value.

Sensitometers provide a systematic series of exposures for the purpose of studying the response of light sensitive materials.

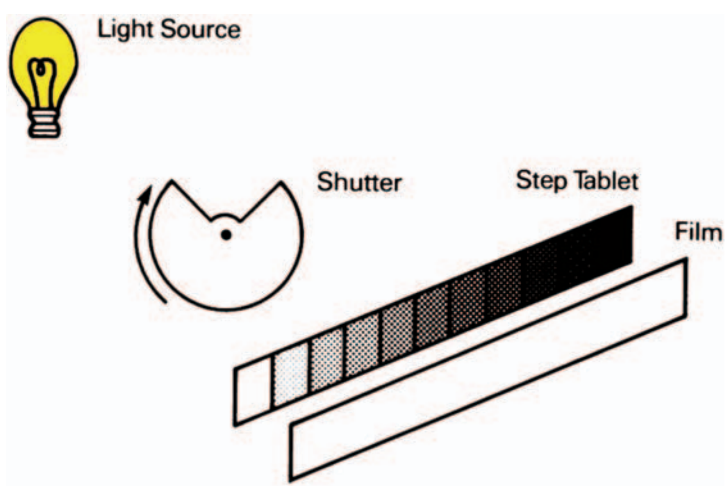


Figure 5-2 The major parts of a sensitometer.

An increase of 0.30 in density in a step tablet produces a decrease in exposure by the equivalent of one stop.

The step tablet serves as the subject for the sensitometer. It converts the single level of light produced by the lamp into many different levels or illuminances simulating the condition in the camera where the film receives varying illuminances due to the tonal differences in the scene.

A step tablet is a series of calibrated filters with uniform density increments. Transmission density step tablets are available in a variety of sizes and formats. The most commonly used step tablet varies in density from approximately 0.10 to 3.10. When the step tablet is placed in the light path, the light is attenuated over a log range of 3.0 (3.10 − 0.10 = 3.00). Since densities are logarithmic values, the illuminances reaching the film plane will have a log range of 3.0. By taking the antilog of 3.0, we find that the ratio of illuminances will be 1000:1, which means that the highest illuminance is 1,000 times that of the lowest illuminance. With such a step tablet, the film will receive a ratio of illuminances far greater than that typically encountered in the camera, which is desirable for testing purposes.

If the tablet contains 11 different equally spaced steps, there will be 10 increments or intervals. Since the total density range is 3.0, the step-to-step difference can be determined by dividing 3.0 by 10, giving 0.30. This means that the steps get progressively denser in 0.30 increments. The antilog of 0.30 is 2, indicating a 2-times factor change in illuminance and exposure between successive steps (recalling that addition of logs corresponds to multiplication of antilogs). The step-to-step exposure change is equivalent to one stop, and the entire range covered is equal to 10 stops.

The shutter in a sensitometer performs the same task as the one in the camera: to control the length of time for which the light will strike the film. The shutter in a sensitometer usually is powered by a synchronous motor that operates in a repeatable fashion. A variety of exposure times can be achieved by using differing gear ratios and slit sizes. The actual exposure time should represent the times used in practice. Theoretically, any combination of illuminance and time giving equal numerical exposures could be used if the emulsion response depended only on the total amount of light received. Because the film responds differently to long and very short exposure times, an effect identified as reciprocity law failure (or reciprocity failure or reciprocity effect), an appropriate shutter speed must be selected to avoid the effect or an exposure adjustment will be needed. When the exposing source is a xenon flashtube, the flash duration governs the length of exposure time.

For the most part, photographers do not own or have access to sensitometers. Therefore, the use of a camera for sensitometry is often unavoidable. In this case, a reflection gray scale can be photographed and used as a test object. As seen earlier, reflection gray scales contain tonal values conveniently displayed from light to dark, and they are probably the most common test objects used in photography. Commercially available gray scales have a density range of approximately 2.0, which means a luminance ratio of 100:1 or about seven stops from the lightest to the darkest patch. The actual log values (reflection densities) are usually marked for each patch. If the gray scale has 10 different patches, then the film will receive 10 different exposures when the shutter is tripped.

This approach to sensitometry invariably leads to less precision in the resulting data for many reasons. First,

when the gray scale is photographed, a nonlinear error is introduced as a result of optical flare in the camera, and there is a lack of image illuminance uniformity because of light falloff toward the corners. Further, the lighting of the original gray scale must be uniform and arranged to prevent reflections, including the subtle uniform reflections of light-colored walls or ceilings.

Sensitometers were developed for use with film, not with digital cameras. After all, it would be not be practical to remove the digital sensor from the camera to use it in a sensitometer. For the purposes of sensitometric studies in digital cameras, the use of a properly lit gray scale or the 12-patch OECF target as described previously is the approach most often used. The nonlinear error caused by light falloff of the lens and optical flare can be corrected digitally by photographing an 18% gray card under the same lighting conditions and normalizing the digital values of the gray-scale image with this data prior to printing. This effectively eliminates the problems that are encountered in a film system when this method is used.

Obtaining the proper exposure is key to successfully studying the tone reproduction of a digital camera. The exposure should place the brightest patch of the target at the highest digital count available without causing clipping in the system.

Digital Camera Sensitometry

After obtaining a properly exposed digital image and determining the exposures for each gray patch, there are many characteristics of the camera that can be examined. However, the first step in characterizing a digital camera is to plot the opto-electronic conversion function (OECF). The OECF illustrates how a digital camera converts the luminance at the sensor to digital counts. OECF is the relationship between the log luminance at the focal plane to the resulting digital counts. Log luminance (or also called log exposure) is plotted on the horizontal axis and digital count is plotted on the vertical axis. It would be analogous to a density versus log exposure curve (DLogH) for film, which will be discussed later.

The opto-electronic conversion function (OECF) is the digital equivalent of the density versus log exposure (DLogH) curve for film.

The OECF should start at a digital count of 0 and go to 255 if the camera outputs 8-bit data. For 12-bit data the range would be 0 to 4,095 and for 16-bit data the range would be 0 to 65,635. The OECF plot will have 3 lines on it, one each for the red, green, and blue layers.

Perhaps the simplest analysis to perform is to access the *white balance* of the camera. The white balance was set during exposure so that the white patch had equal digital count values for the R, G, and B layers. If the color balance algorithm is working properly, all three curves should plot directly on top of each other. In a digital system, to produce a neutral that does not have a color cast present in the image, the R, G, and B digital counts would have to be equal. This evaluation should be performed for all modes in which the camera will be used, including preset illuminants and manual white point setting.

The OECF is used to determine the camera's *dynamic range*. The dynamic range can be thought of as the contrast of the scene. To calculate the dynamic range, the lightest point on the OECF is found. This is the point where the illumination first produces the maximum output level for the camera. The darkest point is found at the illumination level where the signal-to-noise

level passes the value of 3. The dynamic range is the contrast between these two points in contrast, *f*-stops, or densities.

The International Standards Organization (ISO) is a nonprofit organization that provides the standard procedure to calculate an ISO speed.

ISO Speed for Digital Cameras

The term *ISO speed* is familiar to all photographers. An ISO speed is a mathematical value that represents the sensitivity of a film or digital sensor to light. An ISO of 200 is twice as sensitive to light as ISO 100 and half as sensitive as an ISO of 400. An ISO's most common use is with an exposure meter for determining the camera settings needed to achieve an acceptable image, negative, or transparency when being applied to film. ISO and exposure have a reciprocal relationship; the lower the ISO, the greater the exposure needed. The general relationship between speed and exposure is provided in Equation 5-1:

$$\text{Speed} = \frac{1}{H} \qquad \text{(Eq. 5-1)}$$

where H = the exposure in lux-seconds to achieve a certain result.

ISO speeds are determined for film and likewise for a digital camera. However, changing ISO speeds in these two systems means two very different things. For a film camera, it means changing to a different film that is more sensitive to light. In a digital camera, changing the ISO does not alter the sensitivity of the sensor. Changing the ISO amplifies the data coming from the sensor, effectively altering the gain of the electronic subsystem of the camera. However, this process amplifies both the image and the noise in the system.

In a digital system, there are two types of ISO ratings: saturation-based (ISO) and noise-based ISO. The saturation-based ISO is used when the photographer has control over the lighting levels such as in a studio. An exposure is selected that would place the highlight just short of the saturation level for the sensor. The noise-based ISO is appropriate when the lighting levels are less than ideal. In low-light situations, where exposures are longer or the ISO is higher, so is the noise level.

The ISO speeds present in a digital camera have been determined by the manufacturer according to ISO standard and are saturation-based speed values. To determine the saturation-based speed, the Equation 5-2 is used.

$$S_{sat} = 78/H_{sat} \qquad \text{(Eq. 5-2)}$$

where H_{sat} is the minimum focal plane exposure that produces the maximum non-clipped camera output signal. The S_{sat} value is then found in Table 5-1 to locate the ISO speed.

The calculation of a noise-based ISO is a much more complicated procedure and is outlined in the ISO 12232:2006(E). To be performed accurately a programming environment such as MATLAB or ENVI's IDL would be necessary. However, the S_{noise} values have been provided in Table 5-1 for comparison purposes.

Note that an ISO speed can only be determined when the standard is followed. However, that does not prevent photographers from calculating a speed for the conditions under which they are going to use the camera. The speed value would be accurate for those conditions, but could not be called an ISO speed.

Film Sensitometry

After the film has been exposed it must then be processed. This is an

Table 5-1 ISO speed, ISO speed latitude

S_{sat}	S_{noise}	Reported Value
$8 < S_{sat} < 10$	$10 < S_{noise} < 12$	10
$10 < S_{sat} < 12$	$12 < S_{noise} < 16$	12
$12 < S_{sat} < 16$	$16 < S_{noise} < 20$	16
$16 < S_{sat} < 20$	$20 < S_{noise} < 25$	20
$20 < S_{sat} < 25$	$25 < S_{noise} < 32$	25
$25 < S_{sat} < 32$	$32 < S_{noise} < 40$	32
$32 < S_{sat} < 40$	$40 < S_{noise} < 50$	40
$40 < S_{sat} < 50$	$50 < S_{noise} < 64$	50
$50 < S_{sat} < 64$	$64 < S_{noise} < 80$	64
$64 < S_{sat} < 80$	$80 < S_{noise} < 100$	80
$80 < S_{sat} < 100$	$100 < S_{noise} < 125$	100
$100 < S_{sat} < 125$	$125 < S_{noise} < 160$	125
$125 < S_{sat} < 160$	$160 < S_{noise} < 200$	160
$160 < S_{sat} < 200$	$200 < S_{noise} < 250$	200
$200 < S_{sat} < 250$	$250 < S_{noise} < 320$	250
$250 < S_{sat} < 320$	$320 < S_{noise} < 400$	320
$320 < S_{sat} < 400$	$400 < S_{noise} < 500$	400
$400 < S_{sat} < 500$	$500 < S_{noise} < 640$	500
$500 < S_{sat} < 640$	$640 < S_{noise} < 800$	640
$640 < S_{sat} < 800$	$800 < S_{noise} < 1000$	800
$800 < S_{sat} < 1000$	$1000 < S_{noise} < 1250$	1000
$1000 < S_{sat} < 1250$	$1250 < S_{noise} < 1600$	1250
$1250 < S_{sat} < 1600$	$1600 < S_{noise} < 2000$	1600
$1600 < S_{sat} < 2000$	$2000 < S_{noise} < 2500$	2000
$2000 < S_{sat} < 2500$	$2500 < S_{noise} < 3200$	2500
$2500 < S_{sat} < 3200$	$3200 < S_{noise} < 4000$	3200
$3200 < S_{sat} < 4000$	$4000 < S_{noise} < 5000$	4000
$4000 < S_{sat} < 5000$	$5000 < S_{noise} < 6400$	5000
$5000 < S_{sat} < 6400$	$6400 < S_{noise} < 8000$	6400
$6400 < S_{sat} < 8000$	$8000 < S_{noise} < 10000$	8000

important step in the sensitometric process. When exposed film is developed, the latent image is amplified by as much as 10 million to 1 billion times. This tremendous amplification ability makes the silver halide system of photography so attractive, where even weak exposures can yield usable images. The result is a system with great sensitivity or, in the photographer's vocabulary, a fast film.

There are four major factors in development—time, temperature, developer composition, and agitation. Agitation is the most difficult to standardize. The temperature of processing baths can be measured to an accuracy of ±1/10° F. The use of a reliable timer allows the length of development time to be controlled to within a few seconds. Prepackaged chemicals have reduced the problems involved in consistent

The four major development factors are time, temperature, agitation, and developer composition.

The laminar layer of used developer on the surface of film during development acts as a barrier to fresh developer.

Correct agitation reduces uneven development.

developer composition. Proper agitation is difficult to achieve because, as we will see, there are at least two functions it must serve, and it must be different for different systems.

One of the critical problems in the development of the latent image to metallic silver is obtaining uniform density in uniformly exposed large and small areas. Variations of density in uniformly exposed areas are usually damaging to image quality and are almost always due to non-uniform development. Proper agitation of the developing solution is the best safeguard of uniformity. Let us examine the effects of developing film with a total lack of agitation. Figure 5-3 illustrates such a stagnant tank condition. The sequence of events is as follows:

1. As the emulsion is immersed, the molecules of developer move around the tank in random fashion.
2. Since the concentration of developing agent is high in the developer and low in the emulsion, a transfer of the developing agent into the emulsion occurs. This transfer is called diffusion.
3. As the developing agent continues to diffuse into the emulsion it becomes attached to silver halide crystals.
4. If the crystals have received an exposure to light, a chemical reaction occurs that produces metallic silver (the image) and developer reaction by-products.
5. The developer reaction by-products diffuse through and eventually out of the emulsion and into the developer solution.
6. Since some of these by-products are heavier than the developer solution, they tend to drift downward and collect on the bottom of the tank, creating an exhausted layer of developer.

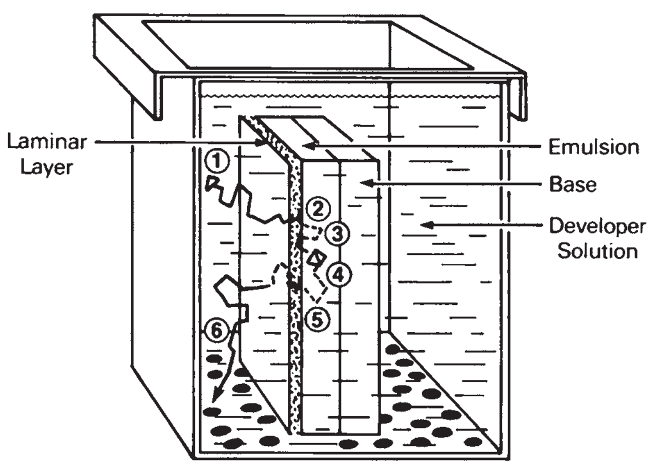


Figure 5-3 Stagnant tank (zero agitation) development. The numbers correspond to the sequence of events described in the text.

Notice that the physical activity is completely based on the process of diffusion—diffusion of developing agents into the emulsion, and diffusion of development by-products out of the emulsion. Clearly, agitation can have nothing directly to do with this process of diffusion, a random molecular activity determined by the temperature and alkalinity of the developer, among other things.

We attempt to control the concentration of chemicals at the emulsion surface by agitation. There is always a relatively undisturbed thin layer of developer lying on the surface of the emulsion that is essentially stuck to the gelatin. This layer acts as a barrier, and as it becomes thicker, the process of diffusion is slowed. This explains why development times must be extended when little or no agitation is used during processing. Because this barrier or laminar layer is not the same thickness everywhere, it explains why improper agitation typically leads to uneven densities in uniformly exposed areas. In order for the barrier layer to be minimized, the fresh developer must make contact

with the emulsion with a fair degree of force. Consequently, excellent agitation is characterized by vigorousness.

An additional function of agitation is to maintain the uniformity of the processing solution's chemical composition and temperature. The agitation motions used should produce a random mix of both fresh and exhausted developer so that every part of the emulsion will have access to developer of the same composition. This is why it is generally not desirable to agitate film in a tray or tank in the same direction every time. The result of such nonrandom, directional movement is a lack of uniformity in the image.

There are many methods to agitate film while developing; in most cases, the typically used methods of tray, tank, and machine processing give acceptable results. However, when problems occur, most likely they are the result of deficiencies in one or both of these two characteristics: vigor and randomness.

Uniformity of development depends to a considerable extent on the degree or time of development. As the development time is increased and gamma infinity (maximum gamma) is approached, variations in time, temperature, and agitation have a decreased effect on image density and contrast. Thus it is more difficult to obtain uniform and consistent development of films that are developed to a low-contrast index (as when photographing high-contrast scenes) than when developing to a higher-contrast index.

Transmittance, Density, Opacity

The most common method for determining the effect of exposure and processing on a sensitometric strip is to measure its light-stopping ability. This

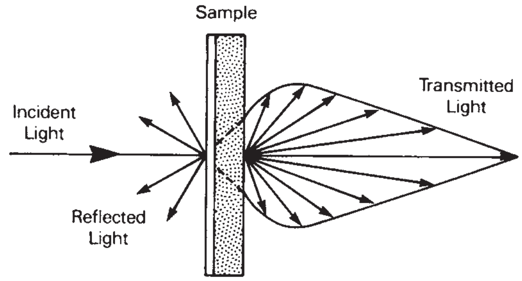


Figure 5-4 Distribution of transmitted light rays caused by light scattering.

information provides excellent insight into the visual and printing characteristics of the image. When light strikes an image on the film, some of it is reflected backwards, some is absorbed by the black grains of silver, and some is scattered (that is, has its angle of travel changed) as a result of bouncing off grains. This is illustrated in Figure 5-4. The light-stopping ability of a silver photographic image is determined by a combination of these three optical occurrences. Notice that the light transmitted through the sample is distributed over a wide angle primarily as a result of the bouncing or scattering effect of the silver grains. For the moment, we will consider only the amount of transmitted light in relation to the amount of incident light on the sample.

Developing film to gamma infinity reduces the unevenness of development associated with poor agitation.

The formulas for Transmittance and Reflectance are similar: *T* = transmitted light/incident light. *R* = reflected light/incident light.

Basically, the transmittance (T) of a sample is the ratio of the transmitted light to the incident light as shown in Equation 5-3.

$$\text{Transmittance } (T) = \frac{\text{Transmitted light}}{\text{Incident light}} \quad \text{(Eq. 5-3)}$$

Consider, for example, the situation in Figure 5-5 where there are 100 units of light incident on the sample, and 50 units are transmitted. The transmittance would be (T) = 50/100, which is 0.50 or 1/2 or 50%. While this approach seems logical and direct, the

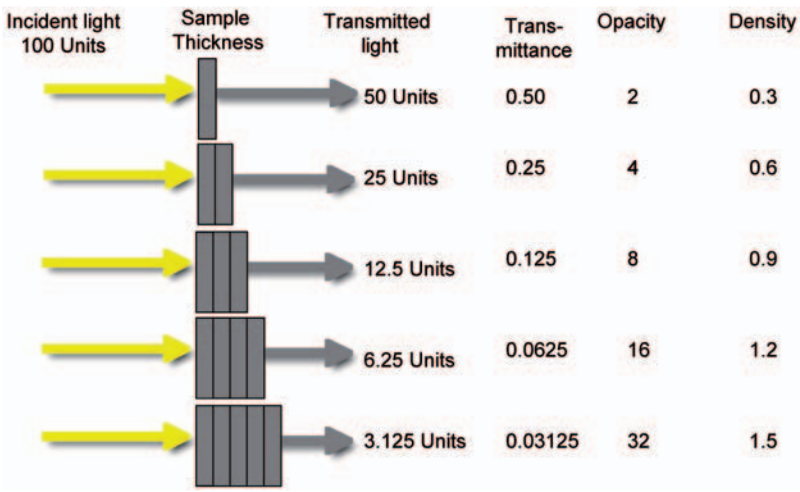


Figure 5-5 The relationship between sample thickness and transmittance, opacity and density.

Density equals the logarithm of the opacity or the logarithm of the reciprocal of the transmittance.

disadvantage is that the transmittance, which describes a sample's light-stopping ability, decreases as the light-stopping ability increases. For samples where the light-stopping ability is great, the transmittance is small.

To overcome this shortcoming, we can calculate the opacity (O) of a sample, which is the ratio of incident light to transmitted light, and thus a reciprocal of the transmittance as shown in Equation 5-4. The formula is:

$$\text{Opacity} = \frac{\text{Incident light}}{\text{Transmitted light}} \text{ or } \frac{1}{T} \qquad \text{(Eq. 5-4)}$$

In the example shown in Figure 5-5, the opacity (O) = 100/50, or 2. Opacity is the reciprocal of transmittance; as the sample's light-stopping ability increases, so does the value for opacity, providing a more logical relationship. However, the potential awkwardness of opacity is revealed when considering the effects of equal increases in light-stopping ability.

Notice that as the thickness of the sample increases (and therefore, the light-stopping ability) in equal amounts by adding one sample atop another, the differences between the opacities are unequal as they become progressively greater. The opacities form a geometric (ratio) progression that becomes inconveniently large as the light-stopping ability increases. For example, ten thicknesses would give an opacity of 1,024.

To compensate for this problem, there is yet a third expression of the photographic effect called density. Density (D) is defined as the logarithm of the opacity (Eq. 5-5).

$$\text{Density} = \log(\text{Opacity}) \text{ or } \log\left(\frac{1}{T}\right) \qquad \text{(Eq. 5-5)}$$

The density of the sample in Figure 5-5 is found as the log of 2, or 0.30.

Figure 5-5 illustrates the relationship of all three values, transmittance, opacity, and density. As the thickness of the sample increases, so do the density and the opacity. The transmittance has the reverse relationship, decreasing as transmittance increases.

The concept of density provides us with a numerical description of the image that is a more useful measure of light-stopping ability. An added benefit is that, as stated earlier, the visual system has a nearly logarithmic response, so our data will bear a relationship to the image's appearance.

Density Measurement

Now that we have considered expressions of the image's light-stopping ability, let us turn our attention to the practical problems of actually measuring the effect. Of the conditions of measurement, two are most important.

The first difficulty involves the measurement of the transmitted light. As shown in Figure 5-4, transmitted light rays form a distribution as a

result of bouncing off the silver grains. This distribution of transmitted light will be wider for coarse-grained images than for fine-grained images because the larger grain size provides a greater surface area over which the bouncing can occur. Consequently, coarse-grained images scatter more light than fine-grained images.

Regardless of the grain size, the basic question is, where should the measurement of transmitted light be made? If, as shown in Figure 5-6, the receptor is placed far from the sample, only light transmitted over a very narrow angle will be recorded—this is called *projection measurement*. Alternatively, when the receptor is placed in contact with the sample, all the transmitted light will be collected, with the angle of collection being very large—this is referred to as a *diffuse measurement*. The projection density will be different from the diffuse density taken from the same sample.

For the companies that design and manufacture densitometers this difference between projection and diffuse density is a major concern, as it is for those who hope to apply their test results to a real picture-making situation. The answer lies in the principle that the testing conditions should simulate those used in practice. Therefore, if the negative is to be printed on a contact printer where the receptor (photographic paper) is in direct contact with the image, then the densitometer to be used should be similarly designed. For those negatives to be projection printed, the receptor will be far from the image, which indicates the opposite condition. These conditions represent extremes from very diffuse to very specular. Almost all commercially available densitometers are designed to provide an intermediate result termed a *diffuse density*.

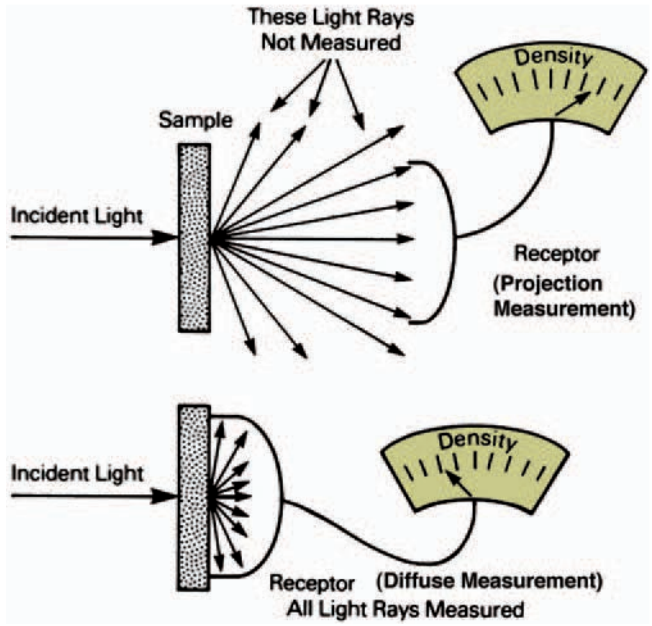


Figure 5-6 Two methods for measuring transmitted light.

It is important to realize that density measurements may come from an instrument that does not exactly simulate the particular photographic system being used. Trial-and-error is usually necessary to determine the appropriateness of the data. The relationship between the diffuse density and the projection density for a given sample may be determined and is called the Callier Coefficient or Q factor. See Equation 5-6.

Exposure meters and densitometers both measure light, but they express the measurements in different units.

$$Q = \frac{\text{Projection density}}{\text{Diffuse density}} \quad \text{(Eq. 5-6)}$$

The second problem associated with the actual conditions of density measurement is the color response of the densitometer. Photocells are typically used in densitometers to sense the light being transmitted. The color response characteristics of all photocells are not alike. Further, the color response of most photocells is unlike that of photographic printing papers. This would not be a significant problem

Most commercial densitometers measure diffuse density, which is between projection density and doubly diffuse density.

The color response of densitometers more closely matches the color response of the eye than that of black-and-white printing papers.

if all the images being measured were perfectly neutral. However, we often measure negatives that are decidedly non-neutral as a result of using a fine-grain developer, a staining developer, or some after treatment of the negative. Indeed, when measuring the densities of color negatives, we never encounter neutral images.

At this point it is appropriate to ask—how will the densities be used? If the purpose is to predict the printing characteristics of a negative, the spectral response characteristics of the printing paper should be simulated. To determine the visual appearance of the image, the spectral response of the human eye should be simulated. In the first case, the result is called a printing density, in the second a visual density. These may be achieved by using certain filters in conjunction with the photocells. All commercially available densitometers are equipped to read visual density (sometimes referred to as black-and-white density). Only those specially equipped with the proper filters will read printing densities.

Characteristic Curves

Characteristic curves provide the relationship between the exposure (input from the subject) that the photographic film or paper received and the densities (the output image) that resulted. The equivalent in the digital environment is the opto-electronic conversion function (OECF) discussed earlier. The OECF provides the relationship between the exposure (input from the subject) that the sensor received and the digital count (the output image) that resulted.

In order to evaluate and understand the results of a sensitometric test, it is necessary to plot the densities occurring on the test strip in relation to the exposures that were received. The data contained in Table 5-2 illustrate the relationship between the input (exposure) data and output (density) data for a sensitometric test of a typical black-and-white negative film. It can be seen that each of the 11 densities produced is the result of a known exposure. The input data are given as both exposure and log exposure. When graphing the relationship, log exposure is used in preference to actual exposure to describe the input values because it tends to conveniently compress the input scale. The use of a logarithmic scale also makes it easier to determine exposure ratios, which are an important part of the evaluation process. Table 5-2 shows that exposures less than 1.0 lux-second are described by negative logarithms. Although the use of logarithms is addressed in Appendix C, it should be noted that negative logs are frequently encountered in sensitometry because the higher sensitivity of modern-day emulsions and digital sensors require only small amounts of exposure to yield image density or digital counts. Consequently, sensitometric exposures of less than 1.0 lux-second are common.

Notice in Table 5-2 that the differences in log exposure are 0.30 each, which is the result of using an 11-step tablet containing step-to-step density differences of 0.30. When plotting the data, actual log exposures or relative log exposures may be used as input data, depending upon what is known about the exposure conditions. The resulting graph will show log (or relative log) exposure on the horizontal axis as input and density on the vertical axis as output. Such a plot is referred to as a characteristic curve or *D*-log *H* curve. Older references call it the H&D curve after Hurter and Driffield, who first described the technique in the

Table 5-2 Relationship between exposure, log exposure, and the resulting density in a set of sensitometric exposures

Density of Original Step Tablet	Actual Exposure (H) (lux-sec.)	Actual Log H	Relative Log H	Step Number	Densities of the Resulting Strip
3.10	0.0064	−2.19	0.00	1	0.18
2.80	0.0128	−1.89	0.30	2	0.25
2.50	0.0256	−1.59	0.60	3	0.39
2.20	0.0512	−1.29	0.90	4	0.54
1.90	0.1024	−0.99	1.20	5	0.78
1.60	0.2048	−0.69	1.50	6	1.03
1.30	0.4096	−0.39	1.80	7	1.28
1.00	0.8192	−0.09	2.10	8	1.55
0.70	1.6384	0.21	2.40	9	1.73
0.40	3.2768	0.52	2.70	10	1.83
0.10	6.5536	0.82	3.00	11	1.85

late 1800s, and later the *D*-log *E* curve. Figure 5-7 shows the curve resulting from a plot of the data in Table 5-2.

The curve in Figure 5-7 is typical of negative-working camera films. It can be conveniently divided into four major sections as follows:

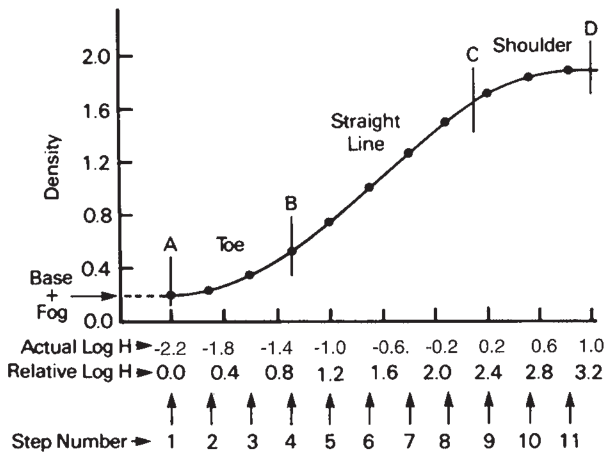


Figure 5-7 The characteristic curve resulting from the data in Table 4-2.

1. *Base plus fog*. This is the area to the left of point A and is the combination of the density of the emulsion support (base) and the density arising from the development of some unexposed silver halide crystals (fog). Here the curve is horizontal and incapable of recording subject detail or tonal differences.
2. *Toe*. This is the section between points A and B and is characterized by low density and constantly increasing slope as exposure increases. Different subject tones will be reproduced as small density differences. It is in this area that shadow detail in the subject is normally placed.
3. *Straight line*. This portion, extending from point B to point C, is a middle-density region where the slope is nearly constant everywhere. It is also here that the slope of the curve is steepest—thus the subject tones are reproduced with the greatest separation (contrast). For many emulsions, however, the middle section of the curve is quite nonlinear, as will be seen later.
4. *Shoulder*. Located between points C and D, this is the portion where the density is high but the slope is decreasing with increases in exposure. Ultimately the slope approaches

The pioneering work by Hurter and Driffield, reported in 1880, laid the foundation for sensitometry.

A change in exposure of one stop, or a ratio of exposures of 1 to 2, corresponds to a change in log exposure of 0.3 on a characteristic curve.

zero, where it is again impossible to record subject detail. Consequently, most of this section is usually avoided when exposing pictorial films.

The characteristic curve displays a "picture" of the film's ability to respond to increasing amounts of exposure as a result of a specific set of development and image measurement conditions. It represents the single most commonly used method for illustrating the sensitometric properties of photographic materials and should be clearly understood.

Determining the Subject Luminance Range

The ability to determine the subject luminance range of a scene will allow the photographer to determine if a scene can be photographed without loss of detail in either the highlights or the shadows. Assume we are photographing the face of a model with highlight and shadow areas, illuminated so that the lighter side has eight times the luminance of the darker side, giving a subject-luminance ratio of 8:1. Since there are now two tones in the scene, there will be two image illuminances and, ultimately, two different exposures with one trip of the shutter. Figure 5-8(A) shows that these two input values will be separated by the log of 8, which is 0.90. If a second photograph is made of this subject, giving one stop more exposure, both log exposures will shift to the right a distance of 0.30 in logs but still will be separated by 0.90 because the subject luminances have not changed, as shown in Figure 5-8(B).

A one-stop change in camera exposure is the same as a 0.30 LogE change.

Therefore, the tones of the subject can be related to the log exposure axis of the characteristic curve. As shown above, the ratio of the subject

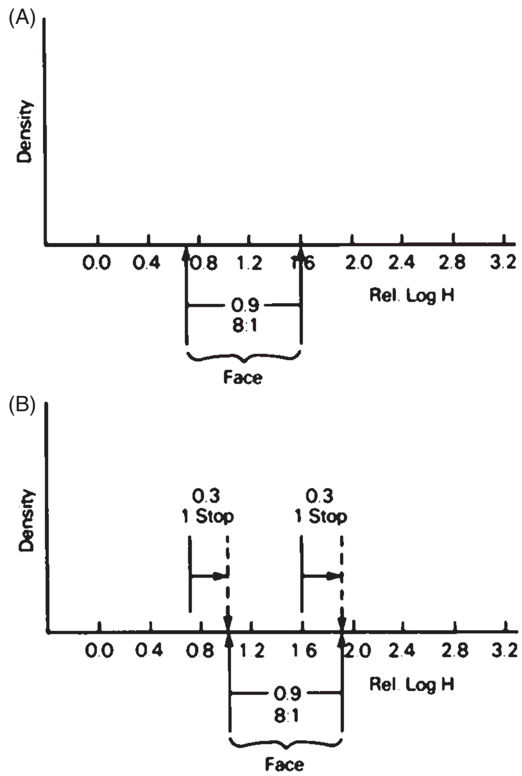


Figure 5-8 Changes in exposure for a simple two-tone scene as related to the log exposure axis.

luminances (highlights to shadows) plays a major part in determining the ratio of exposures (or range of log exposures) the film or sensor will receive. Also, by changing the camera settings or the level of light on the subject, the level of the exposures may be increased or decreased (shifted right or left) on the log exposure axis.

Exposure–Characteristic Curve Relationships

In reference to the simple two-tone scene described above, exposure and processing produced two different densities. The values of the two densities can be found by extending lines up from the two log exposure positions to the characteristic curve and then to the left until they intersect the density axis. This is illustrated in Figure 5-9A, which

shows both log exposures falling on the straight-line section. The actual values of the densities are less important than the density difference because these relate to tonal separation or contrast. Therefore, density differences describe the amount of shadow, mid-tone, and highlight detail in the negative. In this example, the log exposures are separated by 0.90 (an exposure ratio of 8:1), while the resulting densities show a difference of only 0.60. This compression occurs because the slope of the straight-line section is less than 1.0 (45°). The actual slope may be computed by comparing the output density difference to the input log exposure difference. This leads to the generalized form for finding the slope (Eq. 5-7):

$$\text{Slope} = \frac{\text{Density difference}}{\text{Log exposure difference}}$$

$$\text{or } \frac{\Delta D}{\Delta \text{Log } H} \qquad \text{(Eq. 5-7)}$$

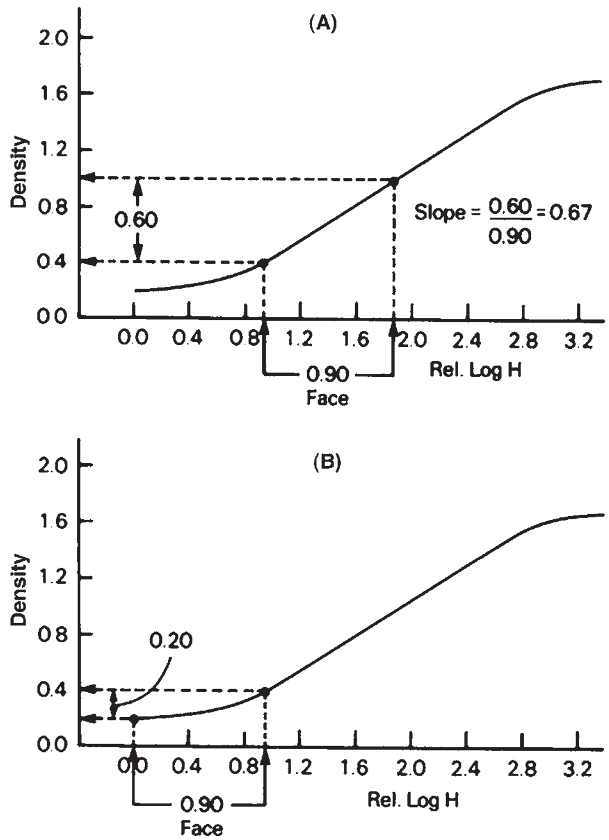


Figure 5-9 Relationship between log exposure and density for two difference sections of the characteristic curve.

For the situation shown in Figure 5-9(A) the ΔD is 0.60 and the $\Delta \log H$ is 0.90—and 0.60/0.90 is equal to 0.67, which is the slope of the straight-line region. This slope is related to the steepness of the curve and describes the rate at which density will increase as a result of increasing the exposure. A slope of 1.0 indicates that a change in log exposure will yield an equal change in density. With a slope of 0.50, the change in density is only half as great as the change in log exposure. The relationship can be restated as follows: Slope relates the negative contrast (density differences) to the subject contrast (log exposure difference). This relationship only applies to the straight-line section of the characteristic curve if indeed there is one.

Where the section of the graph is a curve, as in the toe, there is no simple relationship between log exposure and density. Figure 5-9(B) shows the same two-toned scene placed entirely on the toe portion of the curve. In other words, the subject was given less exposure, as these log exposures are located to the left of the first. The resulting density difference is 0.20, which is considerably less than the first (0.60) because the slope in the toe is quite low. There will be far less tonal separation in this negative than in the first, that is, it has less contrast. If the slope were calculated as before, the resulting number would be related to an imaginary straight line drawn between the two density points and would not describe the actual slopes in the toe, which are everywhere different.

It should be clear that the contrast (density difference) of the negative is affected by changing the camera exposure. This will be the case either when there is no straight-line portion whatever or when the exposures are placed in a nonlinear area such as the toe and shoulder. If the subject tones are placed in the straight-line portion, they will be reproduced in the negative with the greatest possible separation (contrast). As the exposures become less and move into the toe region, the density differences of the shadows will rapidly decrease, and the shadow contrast will be reduced. If the exposures are increased and move into the shoulder region, the density differences of the highlights are quickly reduced, causing a loss of highlight contrast.

Total negative contrast, or TNC, is another name for negative density range.

In practice, the camera is likely to be aimed at scenes that range from about 20:1 to nearly 800:1, with 160:1 being average. Experience shows that excellent negatives are produced when the shadow exposures are placed in the toe of the curve, while the midtones and highlights fall in the midsection as shown in Figure 5-10. The shoulder section is almost always avoided because of the longer printing times required and the resulting loss of image quality. Most camera-speed pictorial films can accept these ranges and give excellent results.

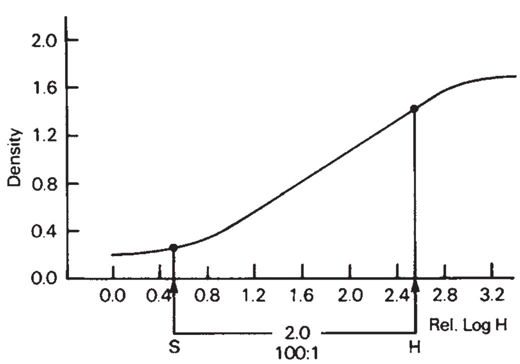


Figure 5-10 Proper placement of log exposures for an average-contrast scene.

Total negative contrast (the density difference between the thinnest and densest areas, also known as the *density range*) is largely determined by:

1. The subject contrast, which determines to a good first approximation the log *H* range on the horizontal axis of the *D*-log *H* curve.
2. The placement of this range of log exposures, determined by the camera settings.
3. The shape of the specific characteristic curve, which is mainly determined by the choice of emulsion and the development conditions.

The total negative contrast is a number similar in concept to the log of the subject luminance ratio. It describes the log range of output (that is, the density range) as a result of the previously mentioned conditions. For pictorial photographic negative emulsions, a total negative contrast of approximately 1.1 is considered normal (for diffusion enlargers) and is based on the printing characteristics of the negative. If the total negative contrast reaches 1.6, the negative is considered to have excessive contrast and probably is unprintable, even on a grade-one paper. When the total negative contrast is on the order of 0.4, it also will be nearly unprintable but because it is too flat for even a grade five printing paper.

Shadow detail, mid-tone contrast, and highlight detail are important, as noted earlier. A negative can have a large total negative contrast and still be totally lacking in shadow detail, as shown in Figure 5-11(A). Likewise, the total negative contrast may be great, but the highlights are blocked up, as in Figure 5-11(B). Thus, we reach again the concept of slope as a measure of contrast in different parts of the

film D-log H curve, and therefore in different parts of the negative (shadows, mid-tones, and highlights). A slope of 1.0 means the subject contrast is exactly duplicated in the negative. A lesser slope means the contrast is reduced, while a larger slope means it is increased. The correct contrast relationship is determined by the way the negative will be used and, in most cases, the way it will be printed, including the grade of paper that will be used. Interestingly, a normal-contrast negative actually has significantly less contrast than the original subject.

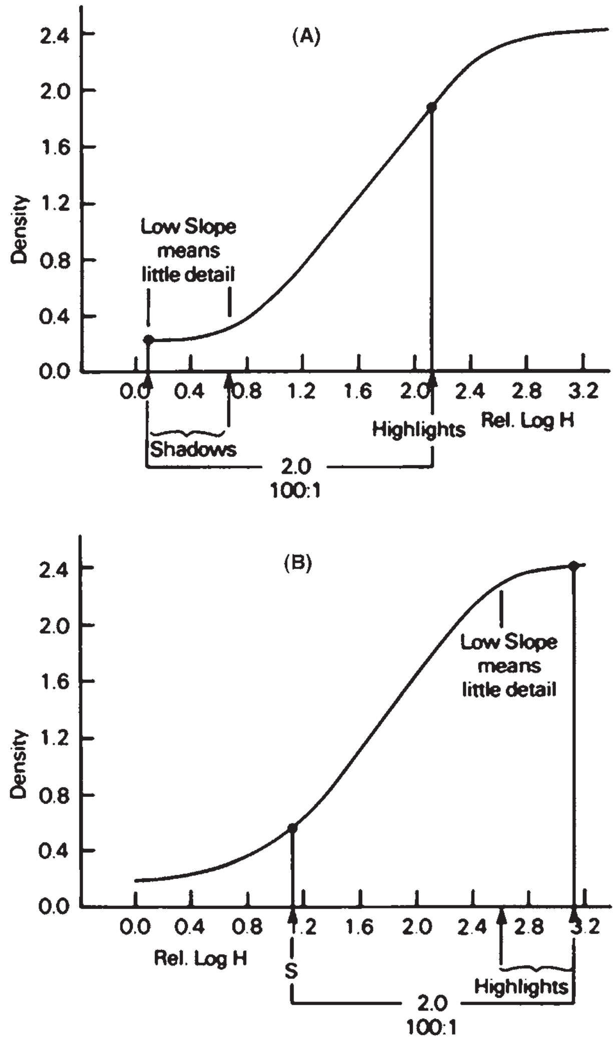


Figure 5-11 The relationship between slopes and density differences for underexposure and overexposure conditions with more than normal development.

Log Exposure Range

In light of the relationship between subject luminances and camera exposures to the densities of the resulting negative, photographers should realize that excellent images can only be made if all the subject tones fall on the characteristic curve where there is sufficient slope. One of the most important measures of the sensitometric properties of the film is the *useful log exposure range*. This is the range of log exposures over which the emulsion can produce adequate separation of densities and is based on the minimum slope required to achieve it. For example, as the camera exposure decreases, the subject tones move farther to the left into the toe and ultimately reach an area where the curve is completely flat (zero slope), resulting in a loss of detail in that portion—typically the shadows—of the negative. The smallest slope necessary to preserve acceptable shadow detail is located at a point on the toe that is the minimum useful point. Experiments using pictorial subjects indicate that the minimum useful point in the toe occurs where the slope is not less than 0.20, as illustrated in Figure 5-12(A). Since the slope of a point cannot be found, the 0.20 refers to the slope of a line tangent to (just touching) the toe. For most camera-speed pictorial films this point of tangency usually falls at a density of not less than 0.10 above the base-plus-fog density and is referred to as the *minimum useful density*.

The location of the maximum useful point on the shoulder is known with less accuracy, partly because proper reproduction of the shadows is more important and partly because the highlight area of most scenes falls short of the shoulder portion.

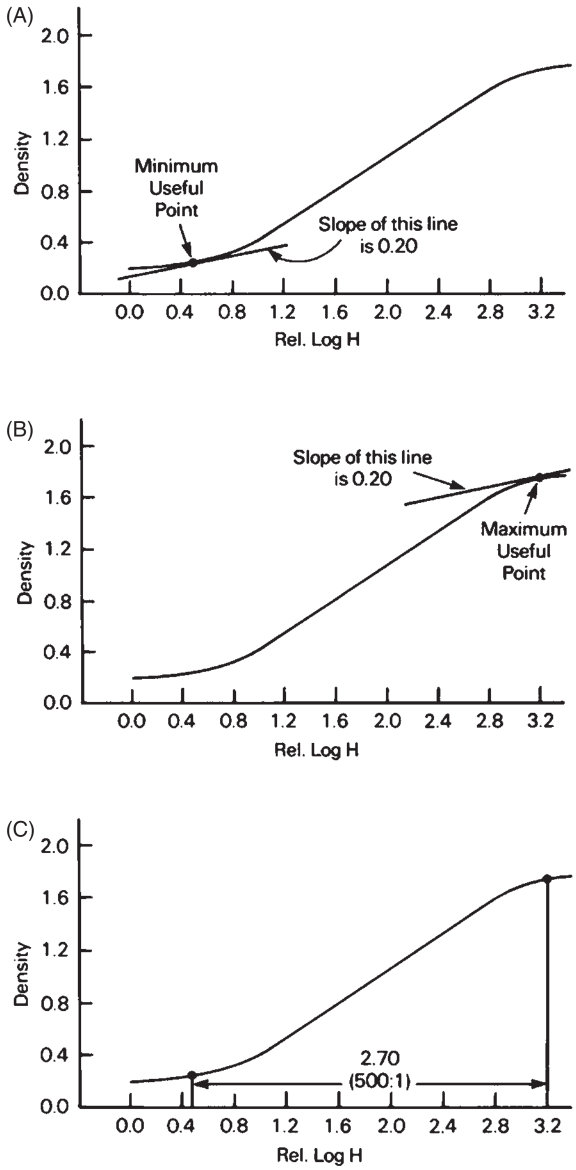


Figure 5-12 Determination of useful log exposure range. (A) Location of minimum useful point (shadows). (B) Location of maximum useful point (highlights). (C) Separation in logs along the horizontal axis (useful log exposure range).

An average outdoor scene has a log exposure range of 2.20 and a luminance ratio of 160:1.

It is safer to overexpose negative film, black-and-white, and color, than to underexpose it.

However, experience indicates that the minimum useful slope on the shoulder is also approximately 0.20 and is found as shown in Figure 5-12(B). Since the shape of the upper portion of the curve highly depends upon the degree of development, no generalization can be made about the maximum useful density for the curve.

Figure 5-12(C) illustrates the concept of *useful log exposure range*, which is the distance along the horizontal axis between the minimum and maximum useful points. In this example, the log range is 2.70, which means the useful exposure ratio is about 500:1 (antilog of 2.70 = 500). As long as the subject tones are placed between these points, the resulting negative will have acceptable detail in all areas. If the ratio of subject tones is so great that it exceeds the useful exposure ratio, either the shadows or the highlights will lack detail in the negative. Consequently, the useful log exposure range is a basic measure of the ability of a given film-developer combination to adequately record the subject tones.

Exposure Latitude

Associated with the useful log exposure range is the concept of *exposure latitude*, which relates to the margin for error in the camera exposure. For example, suppose we were using the film-developer combination resulting in the curve shown in Figure 5-12(C) to photograph a subject with a luminance ratio of 50:1. The subject will provide a log exposure range of 1.70 (log of 50 = 1.70). The useful log exposure range of the film-developer combination is 2.70, leaving a difference in logs of 1.00 (2.70 − 1.70 = 1.00). This means there is a 1.00 log interval *left over* that represents our margin for error. If the darkest shadow in the subject is to be placed at the minimum useful point as shown in Figure 5-13(A), the underexposure latitude is zero, while the overexposure latitude is 1.00 in logs, or a factor of 10, or 3 1/3 stops. When the lightest highlight is to be placed at the maximum useful point, the conditions are exactly reversed as illustrated in Figure 5-13(B). If the subject exposures are placed directly in the

middle of the useful log exposure range as in Figure 5-13(C), the underexposure and overexposure latitude will be equal (1.00/2 = 0.50).

In practice, the shadows of the scene are usually placed at the minimum useful point because this allows for the highest effective film speed. The result is that exposure latitude in the camera is typically overexposure latitude only. Most camera-speed pictorial films have the capability of properly recording scenes with luminance ratios of up to 500:1. As the subject luminance ratio becomes greater, the exposure latitude becomes smaller, which creates a need for more accurate camera exposures. When the subject luminance ratios become excessive (greater than 500:1), special films and developers are required if excellent images are to be produced. The effect of camera flare light on image contrast will be considered later.

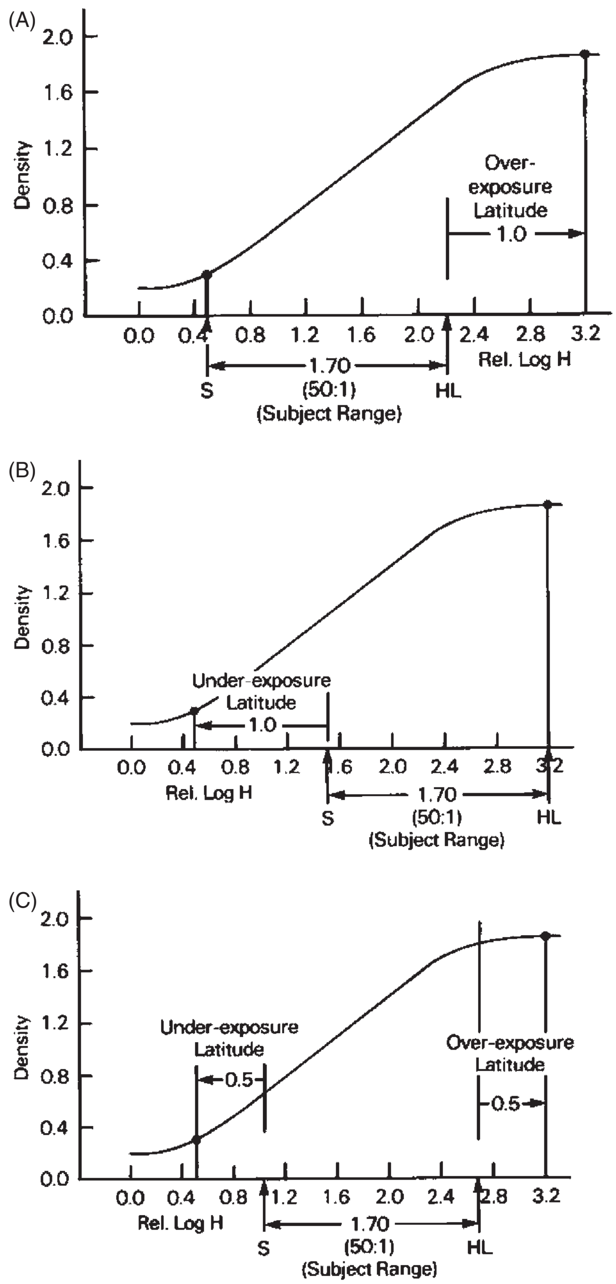


Figure 5-13 Exposure latitude: The relationship between subject log luminance range and the useful log exposure range. (A) Subject exposed for the darkest shadow allows overexposure. (B) Subject exposed for the lightest highlight allows underexposure latitude. (C) Subject placed in the middle of the useful log.

Effects of Development Time

Thus far we have considered only those properties that have been related to one curve and one development time. If a variety of development times are used with some less and some greater than the normal, a family of characteristic curves can be plotted as in Figure 5-14. Notice that all of the curves exhibit the same general shape. The following generalizations may be made:

1. Each curve shows a greater density in all areas as development time increases. Notice that base-plus-fog density is similarly affected.
2. The slope in the toe section is small and relatively unaffected by increases in development.
3. The slope of the midsection increases greatly as development time is increased.
4. The slope in the shoulder remains small for all development times, even

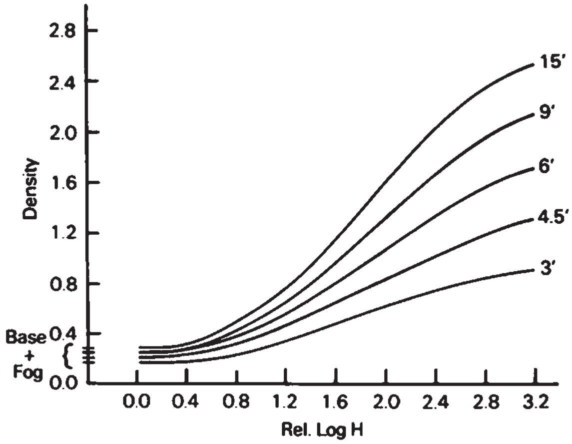


Figure 5-14 A family of curves for five different development times.

though the density level changes dramatically.

5. The useful log exposure range gradually becomes smaller as the development time increases, as a result of the higher slope of the straight line and a more prominent shoulder.

A common saying is to "Expose for the shadows and develop for the highlights."

Subject tones placed in the toe section of the curve will always be reproduced as small densities but, more significantly, with only slight separation of tone (contrast) regardless of the development time. When the subject tones are placed in the middle part of the curve, changes in development time will have a significant effect on the density differences produced. It is in the straight-line region where the photographer has the greatest control over contrast with development. Those subject tones placed in the shoulder section will result in high-density levels, but again with only little separation of tone for all development times.

Gamma = slope = $\Delta D/\Delta \text{Log } H$.

Since most pictorial photographic situations involve only the toe and midsection of the characteristic curve, it can be seen in practice that the darker tones (shadows) should govern camera exposure determination, while the lighter tones (highlights) should govern the degree of development. This idea is consistent with a common saying among photographers: *Expose for the shadows and develop for the highlights*. It should also be apparent that underexposure will shift the shadow tones farther to the left in the toe, where even lengthy development times will not produce a steep enough slope for the detail to be recorded. Further, the increase in development time will adversely affect the mid-tone and highlight reproduction by giving them unacceptably high contrast. This is typically the result when photographers attempt to push their film speed by underexposing and overdeveloping. This condition is illustrated in Figures 5-10 and 5-11(A). Figure 5-10 shows the result of the proper placement of subject tones for a nearly average contrast scene with normal development. Figure 5-11(A) shows the same scene but with the subject tones given less exposure, which places the shadow tones far into the toe region. The steeper slope of this curve is caused by an extended development time with the result being an obvious lack of shadow detail and excessive mid-tone and highlight contrast. The negative could well be unprintable on even the lowest contrast grade of paper.

Gamma

Of the several available measures of the contrast of photographic materials, gamma has the longest record of use. Gamma (γ) is defined as the slope of the straight-line section of the D-log H curve as shown in Equation 5-8. The formula is as follows:

$$\gamma = \frac{\Delta D}{\Delta \text{Log } H} \qquad \text{(Eq. 5-8)}$$

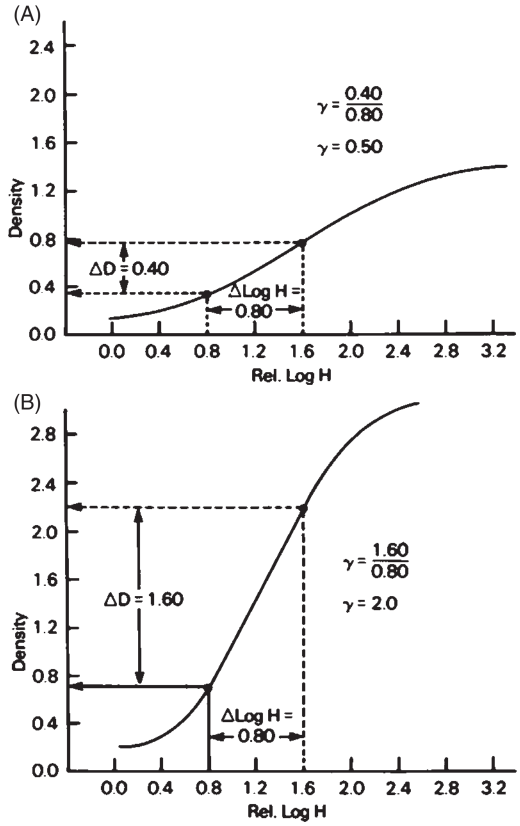


Figure 5-15 The determination of gamma for two different film samples.

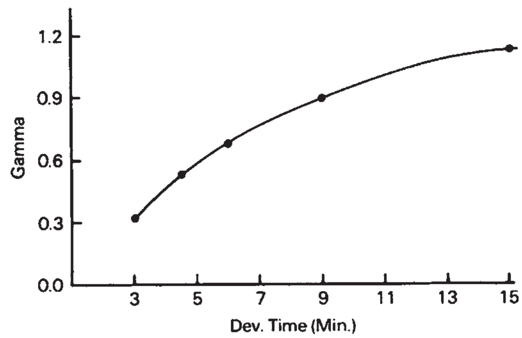


Figure 5-16 Development time vs. gamma chart for family of curves in Figure 5-14.

where ΔD = the density difference between any two points on the straight-line portion of the curve, and ΔLog H = the log exposure difference between the two points chosen.

Examples of the determination of gamma are shown in Figure 5-15(A) and (B) for two different development times. Gamma is an excellent measure of development contrast because it is the slope of the straight-line portion that is most sensitive to development changes. It can also be used to predict the density differences that will result in the negative for exposures that fall on the straight-line section

If the gammas of all of the curves in Figure 5-14 are measured and plotted against the time of development, the curve shown in Figure 5-16 results. This is referred to as a *time-gamma* chart and illustrates the relationship between the slope of the straight line and the development conditions. For short development times, the gamma changes very rapidly, and as the time of development lengthens, the gamma increases more gradually. At some point in time, the maximum gamma of which this film-development combination is capable will be reached. This point is labeled *gamma infinity* and appears to be about 1.10 for these data. Since for this developer gamma increases greatly during short development times, extra care must be taken to minimize processing variability if consistent results are to be achieved. However, if longer times are used, the amount of development time latitude (margin for error in developing time) increases.

It is important to note here that gamma and negative contrast are different concepts. Gamma refers to the amount of development an emulsion receives, while negative contrast is concerned with density differences. Developing to a large gamma does not necessarily mean that a contrasty negative will result. The reason for this is that many factors in the photographic process affect the contrast of the negative, including the subject's range of tones and the placement of the exposures on the D-log H curve.

Gamma is a measure of development contrast, which is only one of multiple factors that determine negative contrast.

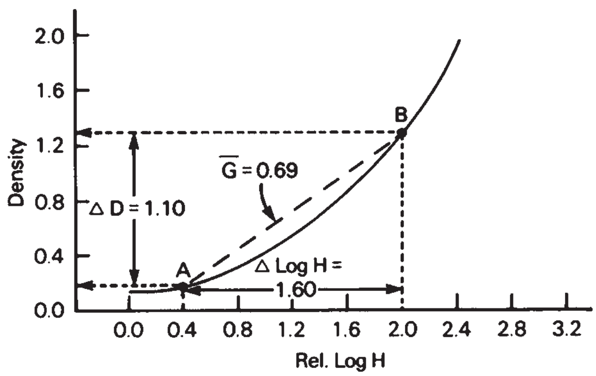


Figure 5-17 Determination of average gradient between two points on the curve.

Contrast index is the average slope of the most useful part of the film characteristic curve.

Average Gradient

In many cases, photographic materials do not provide a straight midsection, and in others there may be two straight-line sections with different slopes. Clearly, a single measure of gamma has little significance for these materials. Even for films exhibiting a single straight line, the useful portion of the curve usually includes part of the toe in addition to the straight line. In these situations where gamma cannot be used as a measure of slope, the concept of average gradient is substituted. An average gradient ($\overline{G}$) is basically the slope of an artificial straight line connecting any two points on the curve, as illustrated in Figure 5-17. The D-log H curve shown here has no straight-line section, but the average gradient can be computed for the artificial line connecting points A and B by using the basic slope formula where slope $= \Delta D/\Delta\log H$. For this example, then: $\Delta D = 1.10$, $\Delta\log H = 1.60$,[1] therefore:

$$\overline{G}(\text{A to B}) = \frac{1.10}{1.60} = 0.69$$

[1] Ilford and Fuji use $\Delta\log H = 1.50$.

The resulting number is a measure of the average contrast over the specified portion of the curve. Notice that this method can produce a variety of slopes by using different sections of the curve. Therefore, when interpreting average gradient data, be careful to note the section of the curve used.

Contrast Index

Another method for measuring the contrast of photographic emulsions is to determine the contrast index of the characteristic curve. Contrast index is an average gradient method with the added feature that the slope is always measured over the most useful portion of the curve. This approach evolved from an evaluation of the printing characteristics of a large number of excellent negatives made on a wide variety of emulsions. The result was a method for locating the most likely used minimum and maximum points on the curve and the determination of the average slope between them.

To determine the contrast index first, to locate a point on the toe that is 0.10 above base-plus-fog density. Using a compass, strike an arc with the center at this point and a radius of 2.0 in logs so that it intersects the upper portion of the curve. Then draw a straight line between these two points and determine its slope. The resulting number will be a close approximation of the contrast index.

In the manufacturer's published data for a film, contrast index is used almost exclusively as a measure of development contrast. This is because contrast index is a measure of the slope over the area of the curve that will most likely be used when the negative is made. Therefore, unlike gamma, contrast index is an excellent

measure of the relationship between the entire log exposure range of the subject and the entire density range of the negative, provided the subject has been exposed on the correct portion of the curve. This means that if the contrast index is 0.50, the total negative contrast (total density difference) will be just one-half the subject log exposure range. For example, an average outdoor scene has a luminance ratio of approximately 160:1 and will provide a log exposure range of nearly 2.20 (log of 160) to the film. A correctly exposed negative, processed to a contrast index of 0.50, will have a total negative contrast of 0.50 × 2.20 or 1.10, and will print easily on a normal grade of paper with a diffusion enlarger.

The important point here is that the required contrast index may be changed to suit the subject log luminance range. Thus if the scene is excessively contrasty, development to a low contrast index will generate a negative that will print on a normal grade of paper. On the other hand, if the scene is unusually flat, the film may be developed to a high contrast index to obtain a normal contrast negative.

ISO Film Speed

Sensitometry in a film system is the measurement of the emulsion sensitivity to light or, more commonly, the film speed. The concept of film speed and its relationship to the determination of the proper camera exposure should be clearly understood because, as we have seen, significant errors in the exposure of the film often cannot be rectified later.

Most pictorial negative films have film speed ratings computed by the manufacturer and published as ISO (ASA) values. This means that the speed has been determined in accordance with the procedures described by the American National Standards Institute (ANSI) and the ISO. Both organizations are nonprofit operations that exist for the purpose of providing standard procedures and practices to minimize variations in testing. Since there are many sources for variation in the determination of film speed, it is highly desirable to have an agreed-upon method that is accepted by a majority as the best technique. The ISO standard for film, just as for digital, provides guidelines for the type of exposing light (daylight), the exposure time (1 second to 1/1,000 second), the developer composition (a formula devised for testing purposes that is not commercially available), the type of agitation, and the amount of development (an average gradient of approximately 0.62) for preparing a film for a speed calculation. Once all these conditions have been met, the speed point is located at a density of 0.10 above base plus fog and the following formula is used:

$$\text{ISO(ASA)} = \frac{1}{H_m} \times 0.8 \qquad \text{(Eq. 5-9)}$$

where: H_m = the exposure in lux-seconds that gives a density of 0.10 above base plus fog, and 0.8 = a constant that introduces a safety factor of 1.2 into the resulting speed value. The film is actually 1.2 × faster than the published value, which guards against underexposure.

ISO (ASA) speeds are rounded to the nearest third of a stop using the standard values listed in Table 5-3. Therefore, each ISO (ASA) speed value has a tolerance of ±1/6 stop. Consider

Film speeds are based on the amount of exposure that is required to produce a specified density.

Table 5-3 ISO (ASA) and ISO (DIN) standard speed values

ASA (Arithmetic)	DIN (Logarithmic)	ASA (Arithmetic)	DIN (Logarithmic)
6	9°	250	25°
8	10°	320	26°
10	11°	400	27°
12	12°	500	28°
16	13°	650	29°
20	14°	800	30°
25	15°	1000	31°
32	16°	1250	32°
40	17°	1600	33°
50	18°	2000	34°
64	19°	2500	35°
80	20°	3200	36°
100	21°	4000	37°
125	22°	5000	38°
160	23°	6400	39°
200	24°		

ISO film speeds are rounded to the nearest one-third of a stop.

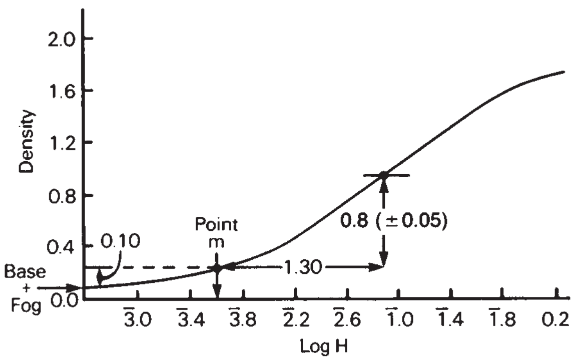


Figure 5-18 The determination of ISO (ASA) speed for a specific sample.

the curve shown in Figure 5-18, which is the result of following the ISO (ASA) standard procedures. The determination of speed is as follows:

1. Locate point m at 0.10 above the base-plus-fog density, which in this case is at a gross density of 0.20.
2. Beginning at point m, move a distance of 1.30 in log units to the right along the log exposure axis.
3. From this position, move up a distance of 0.8 in density units, and if the curve crosses at this point (±0.05), the proper contrast has been achieved and the speed may be computed at point m. If not, the test must be rerun using a development time that yields the proper curve shape.

In this example, the curve shape is correct, and the log exposure at the speed point is −2.6. Taking the antilog of this value, the exposure is found to be 0.00251 lux-second. Substituting, we have:

$$\text{ISO(ASA)} = \frac{1}{0.00251} \times 0.8 = 318.48$$

Using the values in Table 5-3, the ISO (ASA) speed would be expressed as 320. The manufacturer's published values for a given film type are determined by sampling many emulsion batches and averaging the test results.

Following the ISO standard results in film speeds that mean the same thing for all pictorial negative films regardless of the manufacturer. It also means that a given emulsion has only

one ISO (ASA) speed, and this value cannot be changed as a result of using a special developer because the conditions of testing have been specified. Any change in these conditions means the standard has not been followed, and, therefore, by definition the ISO (ASA) speed cannot be found. In practice, most photographers will necessarily use conditions different from those outlined in the standard. For example, if tungsten light is used or a special-purpose developer tried, the circumstances of practice no longer match those of the test. This is an unavoidable pitfall of the ISO (ASA) published speeds—once the best method has been agreed upon and standardized, the speeds are only valid for those conditions. It is common for film manufacturers to publish both daylight and tungsten speeds for some non-panchromatic emulsions.

Separate daylight and tungsten film speeds are published for some films.

Analysis of Negative Curves

When surveying the wide variety of black-and-white negative working emulsions available, it becomes an imposing task to describe the properties of each. Fortunately, this diverse collection of emulsions can be organized on the basis of contrast (as seen in the curve shape) and film speed. Although there are other considerations for the grouping of films, such as format and image structure, it seems appropriate at this point to consider the sensitometric properties, as they have the greatest influence upon the intended use of the emulsion. Negative-working films can be categorized as normal-contrast films, continuous-tone copy films, or line-copy films.

Normal-contrast films are intended to be used with pictorial subjects with the final product being a reflection print. They will have a contrast index of approximately 0.60 when developed normally. The ISO of these films will typically range from 32 to 4000.

The characteristic curves of normal-contrast films can have long or short toe areas. A short toe film will not tolerate underexposure well, as shadow detail will be lost quickly, whereas long toe films are more forgiving in this area. The midsection area of these films is seldom straight so small changes in exposure can have a significant impact on mid-tone and highlight contrast.

Continuous-tone films are used to duplicate photographic prints and artwork and when creating a positive transparency from a negative or vice versa. These subjects are inherently low in contrast as we have already seen. To compensate for this and to attempt to avoid further loss of dynamic range, continuous-tone copy films have a slope of 1.0 or higher. The steep slope of these films means they have very little exposure latitude.

Finally, line-copy films are used to copy line drawings or printed text (sometimes referred to as line-copy of lithographic materials). When we view printed text, like you are looking at right now, we see a white page and black letters. In reality, the print is dark gray and the page in not pure white. To obtain a high-contrast image, line-copy films are extremely high in contrast having a slope of 5.0 or above. As a result, these types of films have almost no exposure latitude.

A contrast index of 0.42 is considered normal for printing with condenser enlargers while 0.56 is considered normal for diffusion enlargers.

Paper Sensitometry

Printing papers differ from the digital world to the emulsion-based world. Emulsion-based photographic papers are available in many variations. They are made in multiple grades or

For normal contrast tone reproduction, film curves have an average slope of less than 1.0 and printing paper curves have a slope of more than 1.0.

contrasts or in a poly-contrast option that uses poly-contrast filters to determine the final grade of the image. In the digital world, there are inkjet prints and laser prints. All paper types can have a variety of finishes that range from high gloss to matte.

Digital print sensitometry is considered to be simpler than its emulation-based counterpart by most. The final output is controlled through the use of color management as opposed to the emulsion-based paper that is influenced by grade selection, development time, developer, agitation, and temperature. A digital image can be manipulated with image editing software to adjust scene contrast, brightness, color balance, even dodging and burning specific areas and proofed on a computer monitor prior to sending the final image to the printer. The same image manipulations can be achieved in a darkroom, but usually with much more effort and time.

The sensitometric analysis that is performed on inkjet and laser prints is minimal. The typical information published is ISO brightness, opacity, and gloss factor at 60°. However, some measurements can be done on both, such as total density ranges and resolution. Emulsion-based photographic papers can have an ISO paper speed calculated, but there is no equivalent value for an inkjet or laser print paper.

Photo-grade inkjet media can produce the same quality image as an emulsion-based photographic paper.

Inkjet Papers

There are two types of inkjet papers: photo-grade media and non-photo-grade media. We are only concerned with photo-grade media. Photo-grade media can further be broken down into three categories. *Resin-coated photo-grade paper* (RC photo-grade paper) is the first, and it has a water-impermeable resin layer beneath the imaging layer. *Resin-coated photo-grade paper* has a barrier layer beneath the imaging layer. Lastly, coated photo-grade paper has a water-permeable layer under the imaging layer. This paper can be cast-coated or micro-ceramic. All three are available in surfaces that range from high-gloss to dead matte. All of these papers have an image-receiving layer that can produce image quality that is of the same quality as emulsion-based paper in regard to resolution, graininess, sharpness, and tone and color reproduction.

ISO Brightness

Brightness is the percentage of light that a paper can reflect—the higher the percentage value, the brighter the paper. Color printed on a paper with a high brightness value will appear to stand out, which is a good quality for photographs. For text, like the page you are reading right now, a lower brightness value would be preferred to reduce eyestrain. Brightness is one of the values that is published for all printer papers.

There are brightmeters that are used by manufacturers to measure brightness. They are designed to ISO specifications. The standard calls for the measuring of the reflectance of blue light. The light has a specific spectral distribution with the peak wavelength at 457 nm. This wavelength was selected because it is the absorption of lignin, which is the glue that holds the fibers of paper together and can give paper a yellow tint. The brightness value provides a measure of the bleaching done to the paper to make it appear white.

Two methods can be used to measure brightness. These methods differ in the measurement geometries. The first is referred to as 45°/0° geometry.

The paper sample is illuminated at a 45° angle and the measurement is made from the perpendicular. The second method uses diffuse/0° geometry and an integrating sphere. In configuration, there are two lamps shining into the sphere, which bounces the light around so that the sample is illuminated with diffuse light. The detector is located perpendicular to the sample to make the measurement.

Optical brighteners in papers absorb ultraviolet radiation and emit the light back in the blue region of the visible spectrum. This extra energy in the blue region negates the yellow in the paper caused by the glues used to manufacture it. The amount of ultraviolet radiation in the light source will affect the brightness as will the amount of whitener in the paper. A brightness measure could also be done on an emulsion-based photographic paper. The reading would be done to an unexposed developed portion of the paper. This is not customarily done; rather a minimum density would be measured.

Gloss Readings

Gloss is an optical property that is caused by the interaction of light with the surface of an object, in this case the print paper. It is the ability that a surface has to reflect light in a specular direction. In photography, paper that is very smooth is referred to as glossy paper, and a paper that has a rougher surface is referred to as matte.

A gloss surface will produce a specular reflection at the same angle that it is illuminated from as illustrated in Figure 5-19(A). A matte surface will also produce a specular reflection, but not as strongly because light is reflected in many directions from the matte as illustrated in Figure 5-19(B). Where the illuminating light is placed and the position that reading is taken will affect the gloss value.

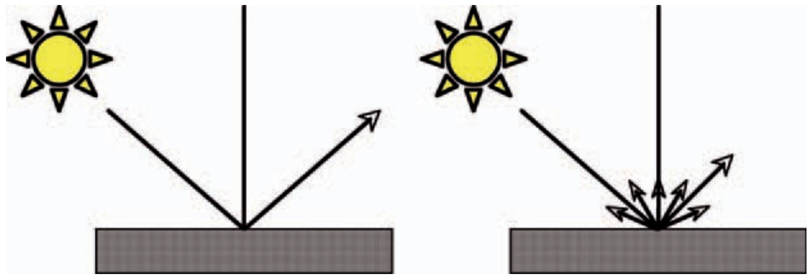


Figure 5-19 (A) A reflection from a gloss surface; (B) reflection from a matte surface.

The specular reflection is measured using a glossmeter. A glossmeter uses unpolarized white light shone through a condenser lens onto the sample. The reflected beam is collected by a receptor lens and measured with a photo detector. The common angles of measurement for glossmeters are 20°, 60°, and 85°. The value published for inkjet and laser printer is the 60° value. This same value could be measured from an emulsion-based photographic paper on an area of unexposed developed paper.

Photographer typically will use inkjet printers for producing high-quality images.

Paper Opacity

Opacity of paper is measured differently from the opacity discussed earlier in this chapter. Paper opacity is a ratio of reflectance measurements. The paper's thickness, type, and amount of filler used during manufacturing, the degree of bleaching the paper received, and the coating that is applied affect opacity.

The reflectance of paper is affected by what is behind it. If a white backing is used, some of the transmitted light will be reflected back through the paper. If the same paper is then placed on a non-reflective black background, its reflectance will be less because

no light that is transmitted will be reflected back through the paper.

To determine paper opacity, the reflectance of a single sheet of paper with a non-reflective black background behind it is measured at a single wavelength, usually 457 nm. A second measurement is made of the paper held against a standard white background or several sheets of the same paper thick enough so that no light is transmitted through them. The opacity is the ratio of the two values expressed as a percentage. Again, here this measurement could be made for an emulsion-based photographic paper from an unexposed developed area of the paper.

Analysis of Photographic Paper Curves

A characteristic curve for a printing paper can be plotted using the reflection densities of a print of a step tablet.

The input range of photographic papers is controlled by the curve slope, which is related to paper contrast grade.

The output range of photographic papers depends primarily on the surface sheen.

The procedures involved in the sensitometric testing of photographic-quality papers are similar to those used for negative materials. The details of the testing conditions are changed to simulate how papers are used. For example, tungsten light is used in the sensitometer because this is the source that most printers use. Also, exposure times are longer (usually between 0.10 and 10 seconds) to approximate those used in a darkroom because reciprocity law failure affects print emulsions as well as films. When a sensitometer is unavailable, a transmission step table may be either contact or projection printed with the actual printer to be used in production. Care must be taken to ensure uniformity of illumination on the easel and accuracy of the timer. If the step tablet is projection printed, optical flare will cause problems similar to those encountered when using a camera and reflection gray scale, as exposure relationships between steps will be distorted. When processing photographic papers, close attention must be given to the details of time, temperature, and agitation because development times are generally short and density is produced quickly.

The common data published for inkjet and laser papers have already been discussed. However, some of the same measurements in the following discussion can also be done with these papers, such as density ranges and minimum and maximum densities. Exposure information and paper speeds do not apply though. To perform density studies, a step wedge can be created on an inkjet or laser printer by printing the image of a photographed step wedge for characterizing the camera's sensor. This would provide an analysis of the entire system. If only the paper is of concern, a digital step wedge image can be created with image editing software and printed.

Reflection Density

In the evaluation of photographic papers, it is necessary to measure reflection densities. Reflection density is defined as the logarithm of the reciprocal of reflectance (R), where:

$$\text{Reflectance } (R) = \frac{\text{Light reflected from the image}}{\text{Light reflected from the base}} \quad \text{(Eq. 5-10)}$$

Thus, reflection density is defined as

$$(D_r) = \text{Log}(1/R) \quad \text{(Eq. 5-11)}$$

The design of a densitometer that measures reflection density necessarily differs from that of a transmission instrument. Since prints are usually illuminated at an angle of approximately 45° and viewed on a plane

nearly perpendicular to the image, ANSI has standardized this illumination and collection geometry, and all reflection densitometers are based upon it. If the instrument is zeroed on an unexposed, developed, and fixed-out piece of photographic paper, the base plus fog automatically will be subtracted from all future readings. When the instrument is calibrated on a reference white such as magnesium oxide, the readings will include the base-plus-fog density. Both approaches are commonly used.

Paper Characteristic Curves

Figure 5-20 contains a characteristic curve typical of a photographic paper emulsion. The major differences between this curve and that of a pictorial film are as follows:

1. The toe portion is usually longer and extends to a higher density.
2. The slope in the midsection is much steeper, and the straight-line portion is short if present at all.
3. The shoulder quickly reaches a maximum density, which is seldom more than 2.1.

Because of these conditions, the useful log exposure range of photographic paper is substantially less than that of pictorial film. However, the purpose of photographic paper is to receive the transmitted tones of the negative as input, while the purpose of negative film is to receive the reflected tones of the original scene as input. When evaluating the contrast of photographic papers, two types of information are important—the total density (output) range and the useful log exposure (input) range.

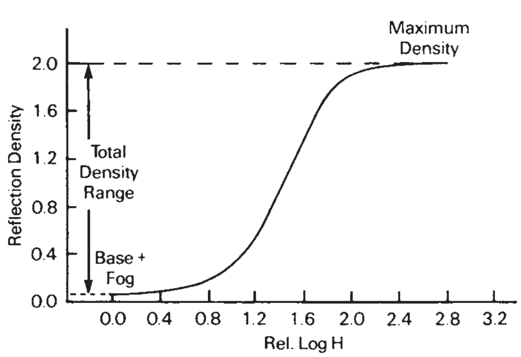


Figure 5-20 Typical characteristic curve for a black-and-white photographic paper.

Paper Contrast

The *total density range* of a paper is the range from paper base plus fog to the maximum obtainable density (sometimes called maximum black) at the top of the shoulder, as illustrated in Figure 5-20. The minimum density (base plus fog) is determined by the whiteness of the support and the fog picked up during processing. Reflection densities of 0.01 to 0.03 are typical minimum densities. The maximum obtainable density is in part governed by the emulsion type but primarily controlled by the print's surface characteristics. A paper with a high-gloss surface can give a maximum density of about 2.10, whereas some papers identified as "glossy" may produce a density no higher than 1.90. Resin-coated papers seldom exceed 2.0. Matte surface papers show a maximum density of about 1.60.

A total density range could also be determined for an inkjet or laser photo-grade paper, although these values are not commonly provided in the manufacturer's literature. The minimum densities are similar to emulsion-based papers. The maximum density achievable with current inks can get as high as a density of 3.0 with a high-gloss surface.

The limit on print density is associated with first-surface reflections,

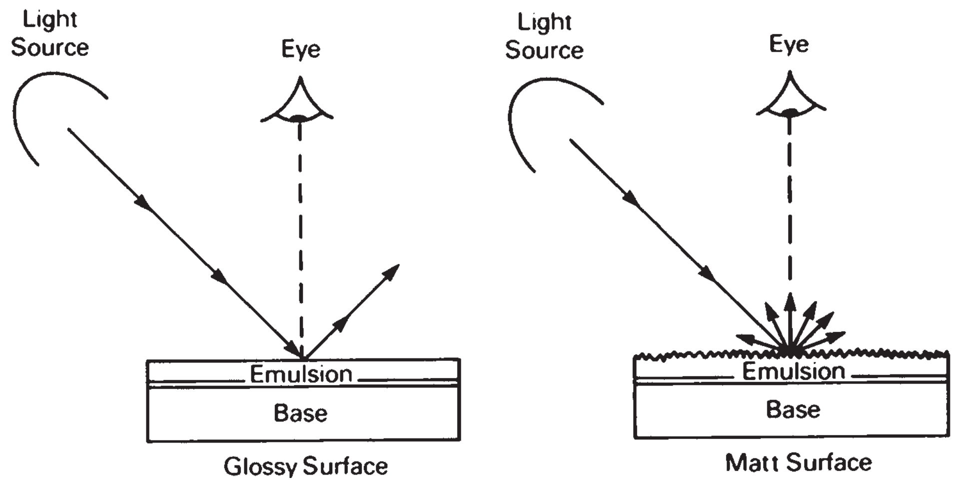


Figure 5-21 First-surface reflection properties of glossy and matte surface papers.

as shown in Figure 5-21. In a typical print-viewing situation, the print is illuminated at 45° and viewed on the perpendicular. For the maximum black patch with the glossy surface, the first-surface reflection is very directional, with the angle of reflectance nearly equal to the angle of incidence. With the eye positioned as shown, the fraction of the light being reflected will not be detected. Since the incident light is either absorbed by the image or reflected at an angle where it is not readily seen, the patch appears black and consequently has a high density. When considering the maximum black patch with a matte surface, it can be seen that the first-surface reflection is quite diffuse and some light will be reflected back to the eye regardless of the viewing angle. The result is a lightening of the maximum black and a corresponding loss in maximum density. The effect on curve shape of different surfaces for the same grade of paper is shown in Figure 5-22, which demonstrates that the greatest change occurs in the shoulder. The practical consequence of this condition is that the output range of a photographic paper is controlled primarily by the surface characteristics.

Increasing the developing time of black-and-white papers beyond the minimum recommended time has little effect on the slope of the characteristic curve.

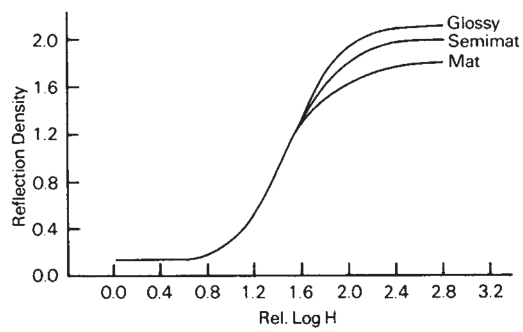


Figure 5-22 The effect of surface characteristics on the curve shape for the same grade of paper.

Unlike the negative film emulsions studied previously, the contrast of photographic papers is not readily controlled by development. Because development occurs rapidly as a result of using a high activity developer, the basic curve shape is essentially determined after a brief period. The curves in Figure 5-23 result from varying development time, with 1½ minutes considered normal. Although it is apparent that the slope of the curves is changing, development times less than 1 minute tend to give a lowered maximum density with a mottled appearance and, therefore, unusable images. At a development time of 1 minute the curve shape is nearly fixed, with

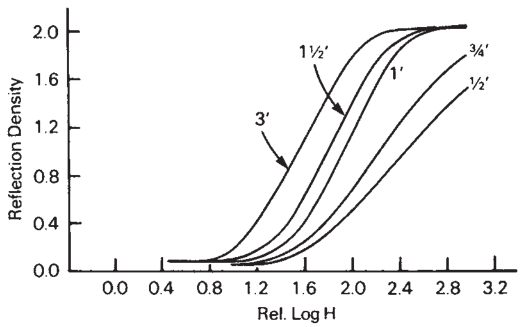


Figure 5-23 The effect of different development times on curve shape for the same grade paper.

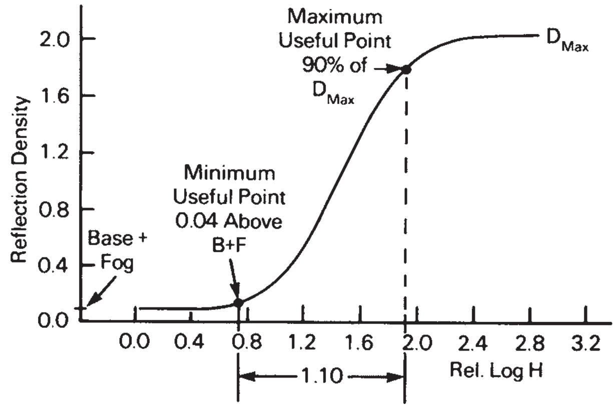


Figure 5-24 The location of minimum and maximum useful points, and the resulting useful log exposure range.

increases in development time merely shifting the curve to the left. Thus extended development times don't change the contrast of photographic papers but do increase the speed up to about one stop. If the development time becomes too long, the fog density increases and makes the highlights appear unacceptably gray.

The effects of changing development time on photographic papers may be summarized as follows:

1. Underdevelopment is to be avoided because of the lack of maximum black and the possibility of mottling.
2. Overdevelopment can be used to increase the speed by as much as one stop, but care must be taken to avoid an unacceptable increase in fog density, which ruins the white areas of the print.
3. Since the curve shape is determined early in development, changes in development conditions cannot compensate for an incorrectly chosen grade of paper.

Thus far in our analysis of photographic paper curves we have only considered the output (density) characteristics. To evaluate the input properties requires a determination of the paper's useful log exposure range. As with camera films the minimum and maximum useful points must be located on the curve. The location of these points is based upon the visual quality of the highlights and shadows produced in the print. Because the tones in the negative are reversed in the print, the highlights are reproduced in the toe area and the shadows in the shoulder of the paper's characteristic curve. Therefore, the minimum useful point in the toe will be based upon proper highlight reproduction. Experiments show that nonspecular highlights in a subject, such as reflections from white surfaces, should be reproduced with a density slightly greater than the base white of the paper. A density of 0.04 above base plus fog is sufficient to give a just-noticeable tonal difference above the base white of the paper, and it identifies the minimum useful point in the toe as shown in Figure 5-24. The base white of the paper is the tone that is reserved for reproducing light sources or the specular (glare) reflections from polished metal or other shiny surfaces. Since these are the brightest parts of the subject, it makes sense that they

should be printed at the lightest tone possible.

When considering the reproduction of shadows and thus the maximum useful point, it is necessary to determine the desired amount of shadow detail. Again, many experiments indicate that black-and-white prints judged as excellent consistently exhibit good shadow detail. Those same experiments show that the maximum density of the print was not used to reproduce the shadow detail. Rather, a point farther down on the shoulder is used where there is sufficient slope for maintaining tonal separation. This point is typically located at a density equal to 90% of the maximum density and denotes the maximum useful point on the curve. However, portions of a scene that are very dark and contain no detail of interest are printed at the maximum density so that they may be reproduced as a solid black in the print. To summarize:

1. The minimum useful point in the toe is based on the reproduction of non-specular highlights and is located at a density of 0.04 above the paper's base plus fog.
2. The maximum useful point in the shoulder is based on the reproduction of shadow detail and is located at a density equal to 90% of the maximum density.
3. The log exposure interval between the two points is defined as the useful log exposure range (sometimes just log exposure range) of the paper. For example, in Figure 5-24 the log exposure range was determined to be 1.10.

Although there are no exposures associated with inkjet or laser papers, the knowledge of shadow and highlight reproduction still applies. Non-specular highlights should be reproduced at 0.4 above paper white. Shadow detail is best placed at 90% of the maximum density the ink or toner can reproduce.

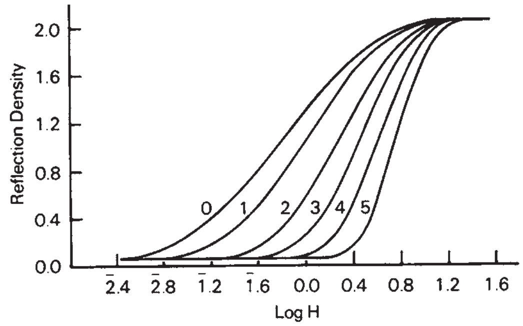


Figure 5-25 Characteristic curves for a family of papers of different contrast grades with the same surface.

Family of Paper Curves

The characteristic curves for a family of papers of different contrast grades are illustrated in Figure 5-25. The major difference between the curves is in the range of log exposures over which they extend. A grade 0 emulsion (sometimes referred to as a "soft" paper) responds over a long range of log exposures, while a grade 5 (sometimes referred to as a "hard" paper) covers a much shorter log range. All of the grades are capable of generating the same output range of densities because they all have the same minimum and maximum densities, assuming the paper surfaces are the same. The contrast grade numbers 0, 1, 2, 3, 4, and 5 represent a system for classifying the contrast of a paper based upon the log exposure range. Some manufacturers use the ANSI standard terms for describing emulsion contrasts. Table 5-4 contains the contrast grade numbers and ANSI standard terms that relate to the log exposure range. Notice that each grade of paper can have a variety of log exposure ranges. For example, a grade 2 paper

Table 5-4 Relationship between paper grade, paper log exposure range, and density range of negatives for diffusion and condenser enlargers

Contrast Grade Number of Paper	ANSI Descriptive Term	Log Exposure Range of Paper	Density Range of Negative Usually Suitable for Each Log Exposure Range or Grade Number (Diffusion Enlarger)	Density Range of Negative Usually Suitable for Each Log Exposure Range or Grade Number (Condenser Enlarger)
0	Very Soft	1.40 to 1.70	1.41 and higher	1.06 and higher
1	Soft	1.15 to 1.40	1.15 to 1.40	0.86 to 1.05
2	Medium	0.95 to 1.14	0.95 to 1.14	0.71 to 0.85
3	Hard	0.80 to 0.94	0.80 to 0.94	0.60 to 0.70
4	Very Hard	0.65 to 0.79	0.65 to 0.79	0.49 to 0.59
5	Extra Hard	0.50 to 0.64	0.64 and lower	0.48 and lower

can have a log exposure range of 0.95 to 1.15, which no doubt explains at least some of the differences between papers of the same grade and surface from different manufacturers.

The American National Standard governing the sensitometric properties of black-and-white reflection print materials specifies the use of the Standard Paper Range Number (R) in lieu of the useful log exposure range. The value of R is determined by multiplying the useful log exposure range (rounded to the nearest 0.10) by 100. For example, if the useful log exposure range for a certain grade of paper is 1.07, it would be rounded to 1.10 and multiplied by 100, giving $R = 110$. The resulting R-value has no standard relationship to the grade numbers assigned by the manufacturers to their products and, therefore, does not reduce the differences between the same grade of paper from different manufacturers.

It should be evident by now that the density range of the negative relates to the log exposure range of the paper it is to be printed on. In fact, the negative's density range actually determines the range of log exposures the paper will receive, and thus the paper grade required. For example,

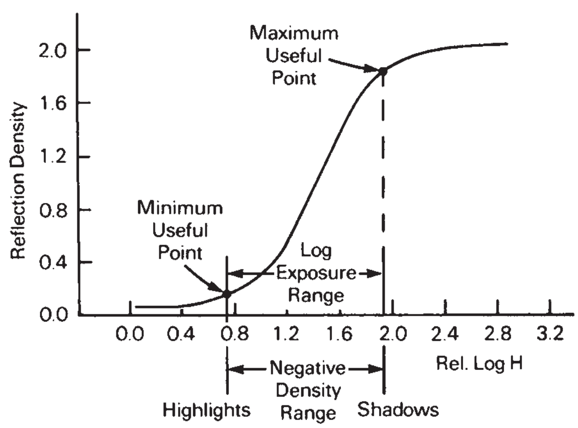


Figure 5-26 The relationship between the density range of the negative and the useful log exposure range of the paper for a correctly exposed print.

a contrasty negative is characterized by a large density range, and so it requires a soft grade of paper that can respond over an equally large range of log exposures.

This situation is illustrated in Figure 5-26, where the density range of the negative is the same as the log exposure range of the paper, and the print has been correctly exposed. The non-specular highlight in the negative will produce a density of approximately 0.04 above the base white of the paper, and the detailed shadow area of the negative will generate a density near 90% of the maximum black.

Prints made on different brands of contrast grade 2 printing papers will not necessarily have the same print contrast.

The best print quality will generally occur when the density range of the negative equals the log exposure range of the paper.

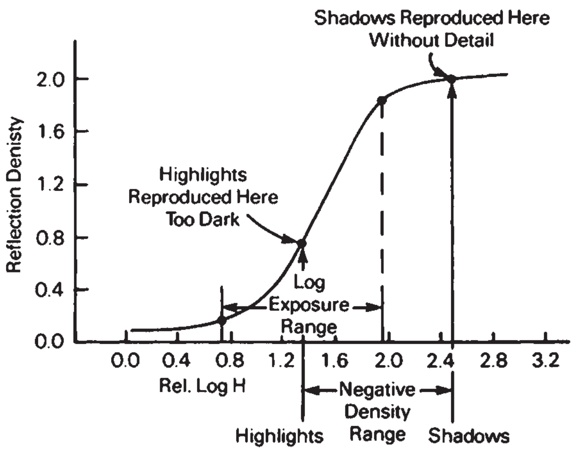


Figure 5-27 Correct match of negative density range and paper log exposure range, with print overexposed by two stops.

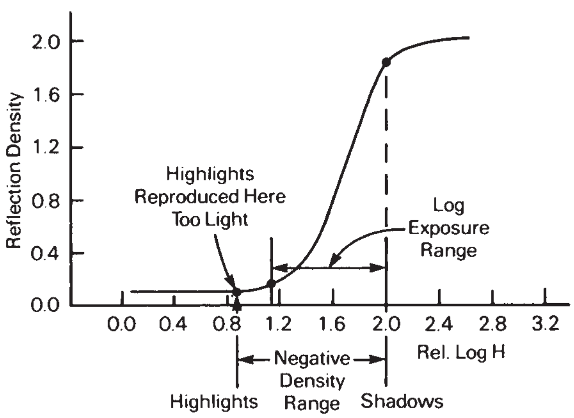


Figure 5-28 Negative printed on a paper grade that is too hard, printed for the shadows.

If the same negative and paper grade were used again, with a two-stop increase in print exposure, the condition illustrated in Figure 5-27 occurs. The result is a print without tonal separation in the shadows, as the shadow densities in the negative are located too far into the shoulder of the paper. Also, the highlights will be too dark because the highlight densities in the negative will print too high on the toe of the paper curve. If the same negative is printed on a grade of paper that is too hard, the condition in Figure 5-28 results. Here the print exposure has been adjusted to give adequate shadow detail, as the shadow densities of the negative are printing at the maximum useful point. However, the highlight densities extend far to the left of the minimum useful point with a complete blocking up of the print highlights. If the print exposure is increased to give better highlight reproduction, the shadows will print too far into the shoulder and begin to block up. Consequently, the odds of achieving a good print with this combination are slim. At this point, we can summarize by saying that for pictorial images, the best print quality will generally occur when the density range of the negative equals the log exposure range of the paper, and the print is correctly exposed.

Condenser and Diffusion Enlargers

The two basic types of enlargers are *diffusion* and *condenser*. The diffusion enlarger employs a large integrating sphere or ground glass to illuminate the negative with scattered light, and is classified as a diffuse system. The condenser enlarger uses a set of lenses (condensers) above the negative so that the light from the bulb will be more concentrated when it strikes the negative, and is thus a specular system. When determining a negative's density range for the purpose of selecting the proper grade of paper, the similarity between the optical designs of the densitometer and the enlarger should be considered.

Since nearly all commercially available densitometers measure diffuse density, the resulting values usually can be directly applied to diffusion enlargers. However, as discussed earlier in this chapter, black-and-white negatives have greater density and contrast in a specular system. Consequently, the densities obtained from a diffuse-reading densitometer

must be adjusted upward to convert them to specular densities. The exact value of this conversion factor (also referred to as a *Q-factor*) will depend primarily on the specularity of the enlarger and is best determined by testing the specific equipment. Many tests of condenser enlargers indicate that this factor is approximately 1.3. This means, for example, that a negative with a diffuse density range of 1.10 will actually have a density range of 1.43 (1.10 × 1.3) in a condenser enlarger. To compensate for this discrepancy, Table 5-4 lists the diffuse density ranges for negatives when printing in either diffusion or condenser enlargers. Notice that the diffuse density range of a negative to be printed on a grade 2 paper in a diffusion enlarger can be between 0.95 and 1.14, while the diffuse density range of a negative to be printed on a grade 2 paper in a condenser enlarger is between 0.71 and 0.85.

The curves in Figure 5-29 show the difference in print contrast between a diffusion enlarger and a condenser enlarger equipped first with an opal bulb and then with a clear bulb, using a negative made on a coarse-grained film.

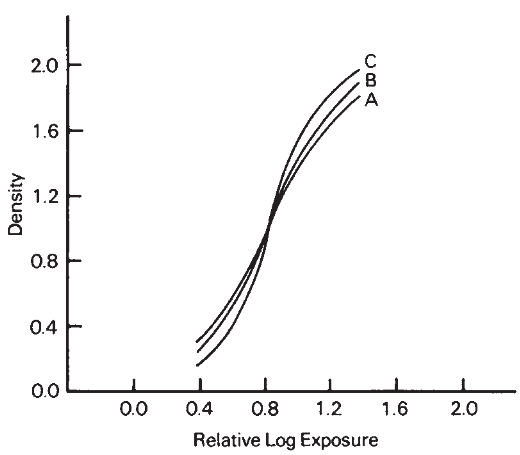


Figure 5-29 Tone reproduction curves for three prints made from the same coarse-grained negative on the same enlarging paper. (A) Diffusion enlarger. (B) Condenser enlarger with opal bulb. (C) Condenser enlarger with clear bulb.

The Effects of Enlarger Flare and Scattered Light

Flare light reduces contrast in the enlarger as well as in the camera. With cameras, shadow contrast and detail are reduced by flare, but with enlargers the highlights are most affected (except with reversal processes).

Flare light in an enlarger originates with the light that bounces around inside the enlarger body and lens before reaching the printing paper as a uniform level of light. The amount of enlarger flare light will vary with the efficiency of the lens coating and the enlarger light-baffling system, and with the proportion of shadow-to-highlight areas in the negative. It will also depend upon whether the opening in the negative carrier is masked down to the area of the negative that is actually being printed. Because enlarger flare reduces the contrast primarily in the highlight areas, it is more damaging to the image quality when it is excessive than camera flare, which reduces contrast mostly in the shadow areas.

To minimize a loss of contrast due to flare light when using an enlarger, the negative should be masked down to the area being printed.

Testing Enlargers for Flare Light

The existence of flare light in an enlarger and its effect on the output density range of the resulting print can be demonstrated easily. A projection print from a step tablet can be made with and without masking off the area around the step tablet. A side-by-side comparison of the prints will reveal differences between the two images. Measuring the density of each step with a reflection densitometer enables the construction of characteristic curves demonstrating the differences graphically, as shown in Figure 5-30.

Enlarger flare light, or intentional flashing, can improve the quality of prints made from contrasty negatives.

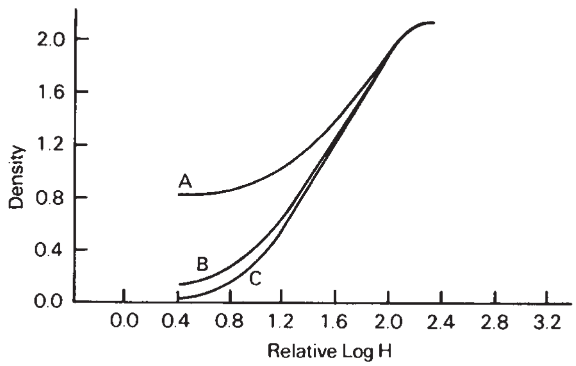


Figure 5-30 Characteristic curves showing the effects of masking off the area around a step tablet in an enlarger negative carrier. (A) No masking. (B) Masked down to a quarter-inch of the step tablet. (C) Masked down to the edge of the step tablet.

Curve A represents a high flare situation in which the area around the step tablet was not masked off. The excess area was masked down to within a quarter of an inch of the step tablet for curve B, and completely masked for curve C. It is evident that the enlarger flare most affects the print's lighter tones, and that the flare density increases dramatically with the size of the unmasked area around the step tablet.

In some prints, the decreased image contrast produced by enlarger flare light results in improved image quality. In these prints, the contrast would have been too high without the flare light. Thus the availability of controlled, variable flare light can be useful.

Paper Speeds

The speed of a photographic paper is inversely related to the minimum exposure necessary to achieve an excellent print. As was shown to be the case in the earlier discussion of pictorial film speeds, experimental evidence indicates that print exposure should be based upon shadow detail reproduction. Since the shadows fall on the shoulder of the paper curve, the maximum useful point, located at 90% of the maximum density, is used as the speed point. The speed is referred to as a shadow speed, with the following formula being used:

$$\text{Shadow speed} = \frac{1}{H} \times 10{,}000 \qquad \text{(Eq. 5-12)}$$

where H = the exposure in lux-seconds needed to generate a density that is 90% of D max, and 10,000 = a large constant that will convert the speed values to a convenient size.

Table 5-5 Speeds for a family of paper grades

Contrast Grade Number of Paper	Shadow Speed	ANSI Paper Speed
0	5000	1600
1	4000	1000
2	2500	500
3	2000	300
4	1600	200
5	1280	160

The shadow speeds of the curves for the family of paper grades illustrated in Figure 5-25 are shown in Table 5-5, which indicates that the shadow speed decreases as the contrast of the paper (paper grade) increases. This means that a grade-4 paper is slower than a grade-2, and appropriate compensation must be made in the exposure time when changing paper grades. The actual speeds of various brands of the same grades of paper will be different, but the general relationship is that the higher the paper grade, the slower the speed.

An alternative method for determining the paper speed is based upon the exposure necessary to produce a mid-tone with a density of 0.60 above base plus fog. This is the current ANSI-standard procedure for deriving the

paper speed and is predicated on the assumption that proper mid-tone reproduction is most important. The resulting speed value is called the ANSI Paper Speed (sometimes ASAP) and is based on the following formula:

$$\text{ANSI Paper Speed} = \frac{1}{H} \times 1{,}000 \quad \text{(Eq. 5-13)}$$

where H = the exposure in lux-seconds needed to generate a density of 0.60 above base plus fog, and 1,000 = a large constant that will convert the speed value to a convenient size.

Table 5-5 shows a comparison of Shadow Speeds and ANSI Paper Speeds for six grades of paper. If print exposure times are based on the speed numbers when changing paper grades, Shadow Speeds will produce matched shadow densities and ANSI Paper Speeds will produce matched mid-tone densities. Some brands of photographic paper show curves similar to those illustrated in Figure 5-31. Since all the curves cross at a density of 0.60 above base plus fog, they will all show the same ANSI Paper Speed. The shadow speed obviously will be different since the position of the shoulder is changing. When printing to a mid-tone with these emulsions, no change in print exposure would be required as a function of changing paper grades. However, when printing for the shadows, significant changes in print exposure would be needed when changing grades. Paper speed numbers can be used to calculate the new printing exposure time when changing from one paper to another. Conversion tables or dials are also available from some paper manufacturers.

Traditionally, low-contrast grades of printing paper have had higher speeds than high-contrast grades.

Analysis of Positive Film Curves

An alternative to printing on photographic paper is to use a relatively high-contrast film, which will yield a positive transparent image that can be viewed by either back illumination or projection. The films used for this purpose are called *film positive emulsions* or *release print films*. They typically have slow speed, very fine grain, and inherently high contrast with gammas varying between 1.8 and 2.8, depending upon the developer formulation and development time. The characteristic curve for such an emulsion is shown in Figure 5-32, where it can be seen that the slope is quite steep.

In principle, the production of film positives from negatives is similar to

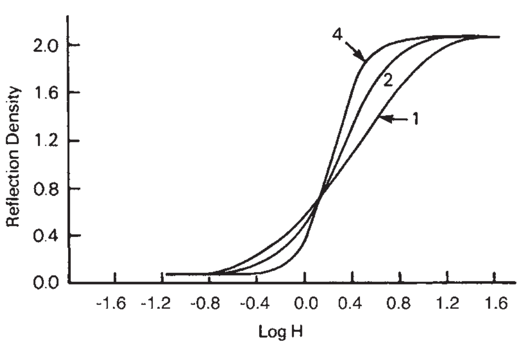


Figure 5-31 Family of paper contrast grades showing the same ANSI paper speed but different shadow speeds.

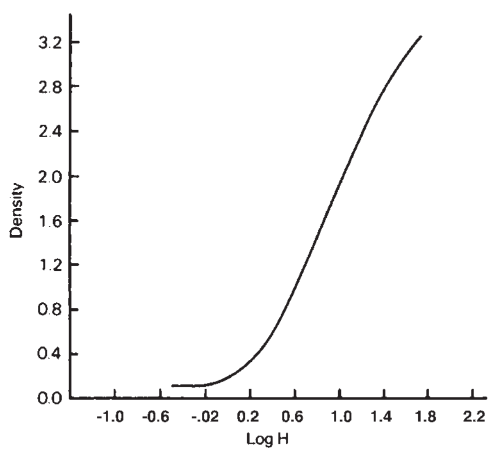


Figure 5-32 The characteristic curve of a film positive emulsion.

Negatives can be printed onto print film materials to obtain positive images on a transparent base that can be viewed by projection or with transmitted light from an illuminator.

that of reflection prints except that the contrast of the emulsion being printed upon can be controlled readily by development. This eliminates the need for various contrast grades. Experience indicates that the minimum useful point on the film positive curve for good highlight reproduction is approximately 0.30 above the density of base plus fog. If the highlights are reproduced with a greater density than this, they appear too dark, and if the density is any less, they look "washed out." Although these films are capable of achieving densities over 3.0, the shadows are best reproduced at densities of 2.7 and less depending upon the contrast of the negative. The larger density range available with film positives is far greater than that of photographic paper allowing subjects with high luminance ratios to be faithfully reproduced. The relationship between the density range of the negative and the film positive curve is illustrated in Figure 5-33 for a correctly exposed and processed image.

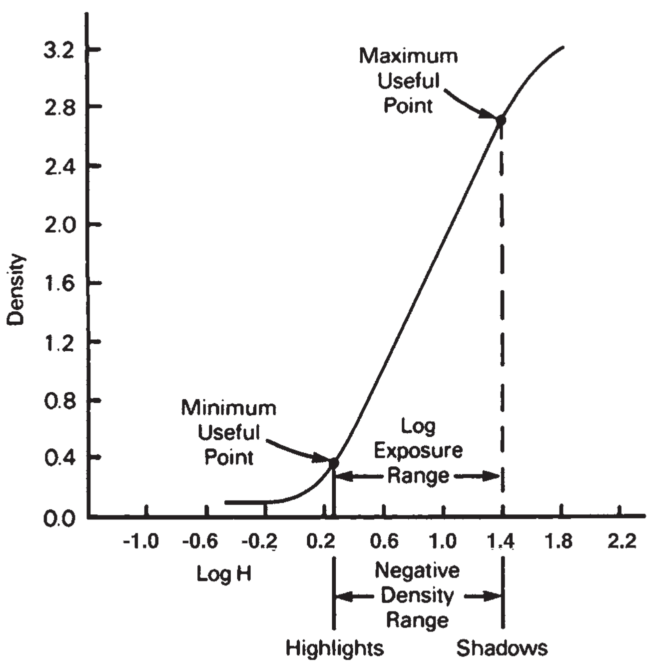


Figure 5-33 The relationship between the density range of the negative and the useful log exposure range of the film positive emulsion for a correctly exposed image.

Notice that the slopes in both the highlight and shadow regions of the curve are greater than those of a photographic paper. The resulting film positive will have greater tonal separation in those areas than a reflection print made from the same negative.

There is no standard method for determining the speed of positive films, but speed points based upon either highlight or shadow reproduction are commonly used to calculate speed values. The highlight method involves determining the exposure necessary to produce 0.3 above base-plus-fog density using the following formula:

$$\text{Speed} = \frac{1}{H} \times 1000 \qquad \text{(Eq. 5-14)}$$

The mid-tone method employs the same formula, except that the exposure necessary to generate a density of 1.0 above base plus fog is used. Shadow speeds are seldom used for these films because the steep slope in the shadow region of the curve assures that good shadow detail will be maintained. Therefore, print exposures are generally based upon either highlight detail or mid-tone density. Regardless of which speed method is used, the speed of film positive emulsions is highly dependent upon the degree of development. Figure 5-34 shows a family of curves for different development times of a film positive emulsion. The curve shifts to the left, indicating an increase in speed, as development time lengthens. Thus close attention must be given to the details of development if consistent results are to be obtained.

By printing on film positive emulsions, the photographer can overcome the single greatest limitation of the negative-positive system—the low maximum density produced by photographic papers. The wider density

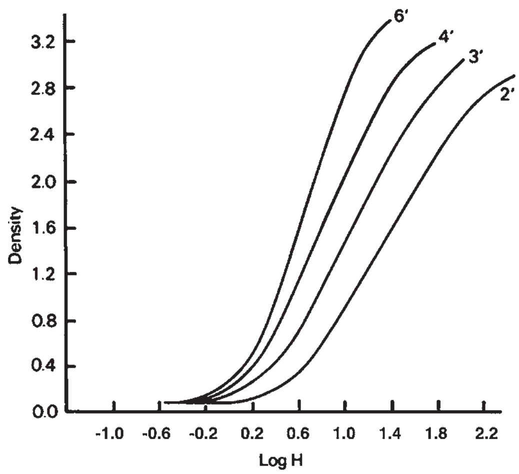


Figure 5-34 Characteristic curves for a variety of development times of a film positive emulsion.

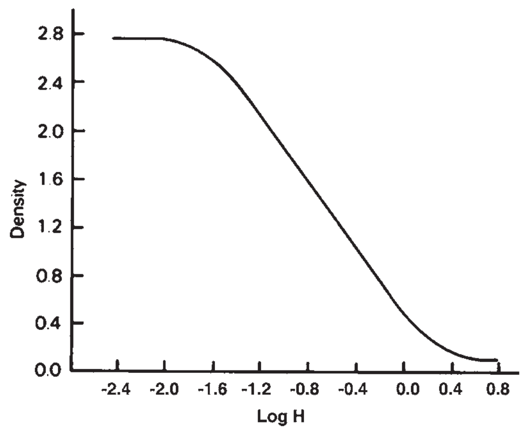


Figure 5-35 Characteristic curve of a reversally processed film.

The basic steps of reversal processing are to develop a negative image, bleach the negative image, fog the remaining silver halides, and develop the positive image.

range of the film positive results in images with greater physical and visual contrast. Not only will the tonal range appear greater, but also the shadows and highlights will have more detail and brilliance. Ideally, film positives should be viewed on a transparency illuminator in a darkened room with the surround masked off to obtain the greatest visual contrast. If the image is placed in a projector and viewed on a screen under typical conditions, the image contrast is drastically reduced as a result of both optical flare and ambient room light reaching the screen. Even under these conditions, the contrast of projected images still exceeds that of reflection print images.

Analysis of Reversal Film Curves

The generation of a positive, transparent image may also be accomplished through a procedure called reversal processing. In this method, a film that was exposed in the camera is first developed to a negative, without fixing. In the next step, a bleach bath dissolves the negative silver image leaving unexposed silver halide in amounts opposite to those of the negative. This unexposed silver halide is exposed (fogged) by flashing to light (or is chemically fogged) and then developed to give the desired positive image. The second development is followed by fixation, washing, and drying. The result is a black-and-white transparency produced on the original film exposed in the camera.

The characteristic curves for reversal materials are plotted in the same manner as those of negative working emulsions except that the direction of the curve is reversed. This is necessary because with reversal materials the density decreases as the exposure becomes larger. Consequently, the shadows and darker tones are reproduced as high densities while the highlights and lighter tones yield small densities. The *D*-log *H* curve for a typical reversally processed film is shown in Figure 5-35. The curve exhibits a steep middle section, which is necessary to give sufficient contrast to the image, since it will be viewed directly. This results in a shortened useful log exposure range, meaning that the exposure latitude is small and scenes with excessive contrast cannot be properly reproduced. In fact, most reversally

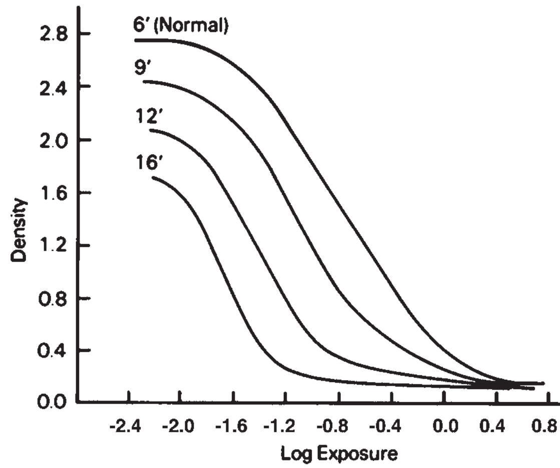


Figure 5-36 The characteristic curves resulting from different first development times for reversally processed film.

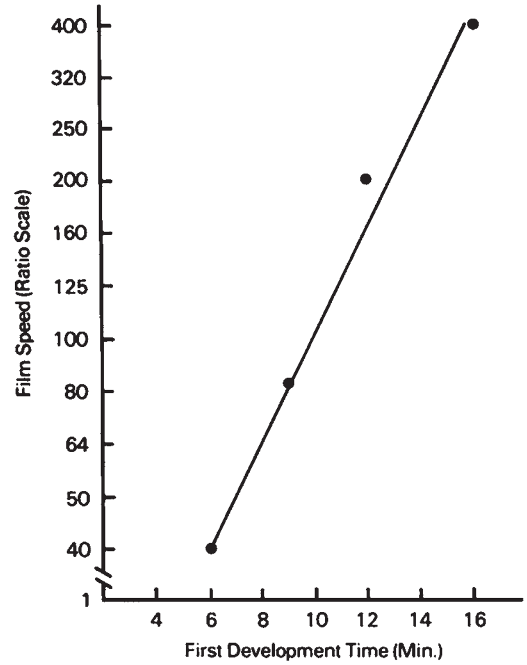


Figure 5-37 First development time vs. film speed for reversally processed film.

processed emulsions do not exceed a 1.90 useful log exposure range. Although many negative-working films may be reversally processed, emulsion manufacturers usually design or designate specific films to be processed using the reversal method.

The influence of processing changes on the curve shape is more difficult to ascertain with reversal processing because there are more major steps involved than with negative processing. The effect of varying the time of first development while all other steps are held constant is illustrated in Figure 5-36. The first development time has a significant effect upon all of the sensitometric parameters of the film. As the first development time is lengthened, the maximum density of the positive image becomes lower due to an increase in the fog density at the negative stage. The minimum density also decreases slightly because of the increase in the shoulder density at the negative stage. Increases in the slope of the curve are most noticeable in the toe region, indicating a small gain in contrast.

The effect on speed of altering the first development time is shown in Figure 5-37. The speed point was located at a density of 1.0 above base plus fog, and the speed was calculated using the following formula:

$$\text{Speed} = \frac{1}{H} \times 10 \qquad \text{(Eq. 5-15)}$$

The graph indicates that the speed of reversally processed films can be increased by up to 10 times by lengthening the time in the first developer. However, the speed increase is coupled with a decrease in the maximum obtainable density, which results in poor shadow reproduction. When the maximum density falls below 2.0 for transparencies, shadow-detail reproduction is usually unacceptable. The increased contrast in the midtones may also contribute to an inferior result.

Introduction to Photographic Effects

Most of the time, the response characteristics of photographic materials and processes are quite predictable, based

on the principles discussed thus far. However, there are conditions where the resulting photographic image does not have the characteristics that were anticipated. Although the making of photographs is a relatively simple task, the response properties of photographic materials are quite complicated. An understanding of conditions that can lead to unexpected results will be most beneficial in mastering the photographic process. Some of these photographic effects are considered in the sections that follow.

Reciprocity Effects

In 1862, two scientists, Robert Wilhelm Bunsen and Henry Enfield Roscoe, proposed a general law for photochemical reactions stating that the end result of a primary photochemical reaction simply depends upon the total energy used, regardless of the rate at which the energy is supplied. Photography involves a photochemical reaction in which light is used to expose film or paper to form a usable latent image, and chemistry is used to develop a visible silver or dye image. The end product (density), however, does not depend simply upon the total energy (exposure), but also on how that exposure is distributed in terms of illuminance and time. For example, two pieces of film can receive equal exposures that may result in different densities because the exposure times and illuminances are quite different. Exposure (H) is a product of illuminance (E) and time (t). An illuminance of 2 lux for 1/100 second produces the same exposure (0.02 lux seconds) as an illuminance of 0.002 lux for 10 seconds. Because the response may be different for these two exposures, the reciprocity law of Bunsen and Roscoe is said to have failed.

Early literature described this situation as *reciprocity law failure* (RLF). Current literature simply refers to it as *reciprocity failure* or *reciprocity effect* to distinguish it from Bunsen and Roscoe's reciprocity law, which holds true for primary photochemical reactions. The law is considered valid for X-ray and gamma ray exposures with silver halide emulsions, and for light exposures with certain non-silver processes such as diazo and selenium electrostatic processes. Reciprocity failure in photography simply means that the response (density) of a photographic material cannot be predicted solely from the total exposure a film has received (except over a small range of exposure times). For pictorial films, the range over which reciprocity failure is negligible is from about 1/10 second to about 1/1,000 second. Beyond these time limits reciprocal combinations of exposure time and illuminance that give the same total exposure will not give the same density response. As an example, if a meter indicates camera exposure settings of *f*/5.6 and 1/30 second, but because greater depth of field is needed the lens is stopped down to *f*/45 and the film is exposed for 2 seconds, the resulting densities will not be the same even though the combinations of camera settings were equivalent. The 2 second exposure will result in a thinner negative. Density will be less for exposure times longer than 1/10 second or shorter than 1/1,000 second. In other words, the film will be underexposed even though the subject was metered correctly, the right camera settings were used, and development was correct. This is an example of reciprocity failure or the reciprocity effect.

In addition to the loss in density already noted, reciprocity failure can change image contrast. The extent of

Photographic effects can produce unexpected responses to exposure of photographic materials.

Low-illuminance reciprocity failure typically results in a decrease in negative density and an increase in contrast.

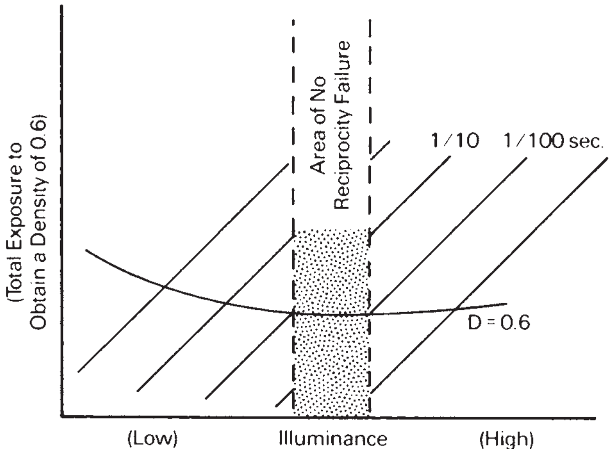


Figure 5-38 Reciprocity curve. A straight horizontal line would represent no reciprocity failure.

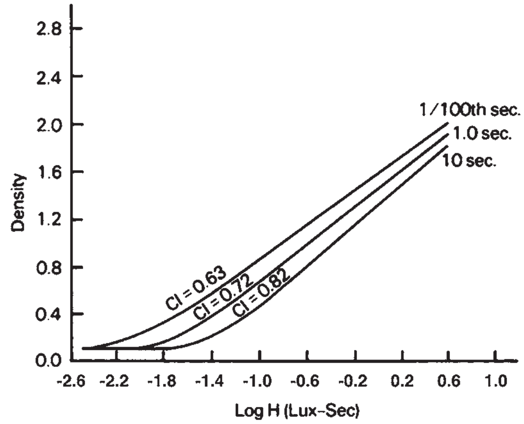


Figure 5-39 Low-illuminance (long exposure time) reciprocity failure.

the changes in density and contrast depends upon the combination of illuminance and exposure time and the characteristics of the emulsion. The reciprocity curve in Figure 5-38 shows the relationship between the total exposure (on the vertical axis) required to obtain a given density of 0.6 and the various combinations of illuminance (horizontal axis) and time (45 lines). If there were no reciprocity failure, the curve would be a straight horizontal line, and the same exposure, regardless of the reciprocal combinations of illuminance and time used, would give the same density. This is true over a limited range of illuminances and times as indicated by the bottom part of the curve, which is almost flat. (Although reciprocity curves will generally differ from one product to the next, they will have the same shape except for certain special emulsions.)

Low-Illuminance Film Reciprocity

Reciprocity failure is often encountered in low-light-level photography, and it is commonly the reason for thin, underexposed negatives. The sensitometric effect of low-illuminance reciprocity failure for a pictorial film can be seen in Figure 5-39. All three films were given the same exposure, employing reciprocal values of illuminance and time to allow the use of three different exposure times. The same conditions of development were used for each. If there were no reciprocity failure, the three curves would have the same shape and be superimposed. The fact that the 1-second and 10-second curves are displaced rightward indicates a progressive loss of film speed as the exposure time increases. In other words, when using exposure times of 1 second and longer for this emulsion, additional exposure is required to obtain the expected image density.

Adjustments need to be made in development as well as exposure for long exposure times at low light levels. The reason for this can be seen in Figure 5-39. In addition to the displacement of the curves, the curves differ in slope.

As the exposure times reach 1 second and longer, there is a significant increase in slope and thus image contrast. Whereas an exposure time of 1/100 second with normal development produced a contrast index of 0.63, an exposure time of 10 seconds with the same normal development produced a negative with a contrast

index of 0.82—about a 30% increase in contrast. This is caused by the fact that low-intensity reciprocity failure affects the lower density areas more than the higher density areas. Thus, in order to obtain the expected image contrast in the negative, a reduction in development is necessary. Because altering the degree of development also affects density, the reciprocity failure exposure factor will be larger than it would be if the degree of development is not adjusted for the anticipated increase in contrast with long exposure times.

Low-illuminance reciprocity failure requires an increase in exposure along with a decrease in development to adjust for contrast. If only the exposure correction is made, the negative may have to be printed on a lower grade of paper than usual to adjust for the increase in contrast index of the negative.

High-Illuminance Film Reciprocity

Exposure of films for times shorter than 1/1,000 second, as with some electronic flash units, results in decreased density. The decrease is largest in the highlight areas, with negative type films producing a lower-contrast image. An exposure increase and an increase in development are both needed to compensate for this.

The characteristic curves in Figure 5-40 illustrate the effect of high-illuminance reciprocity failure. All three films received the same total exposures, using reciprocal values of illuminance and time to obtain shorter exposure times. Development conditions were kept constant. Notice that the 1/10,000- and 1/100,000-second curves are also displaced rightward, indicating a loss of film speed. It is important to notice that under these conditions the curve shape changes in a manner opposite to that with low illuminance. Specifically, the slope of the curve decreases at exposure times of 1/10,000 second and less, indicating a loss of contrast. Observe, however, that contrast increases with increasing exposure time, for both low-illuminance and high-illuminance reciprocity failure. If only an exposure adjustment is made, the negative would have to be printed on a higher contrast

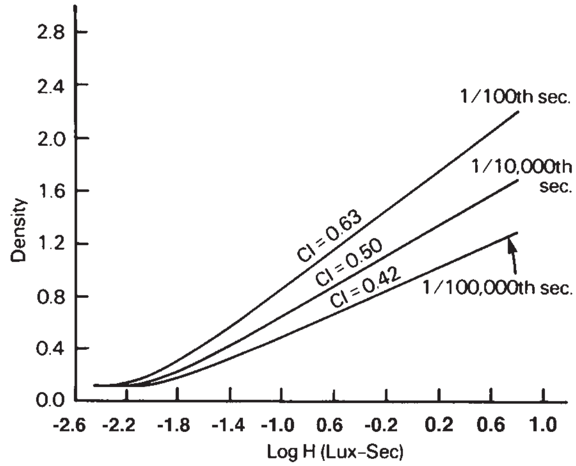


Figure 5-40 High-illuminance (short exposure time) reciprocity failure.

High-illuminance reciprocity failure typically results in a decrease in negative density and contrast.

Black-and-White Paper Reciprocity

Reciprocity effects are exhibited by all photographic emulsions and can be seen easily by printing on any photographic paper and using a series of increasing exposure times, as shown in Figure 5-41. A photographic step tablet was first printed at a relatively short exposure time of 10 seconds at *f*/5.6, and then for each subsequent print the exposure time was increased as the illuminance was proportionally decreased by stopping the lens down and adding neutral density filters. The density decreased progressively even though each test strip received the same series of photographic exposures—as the illuminance

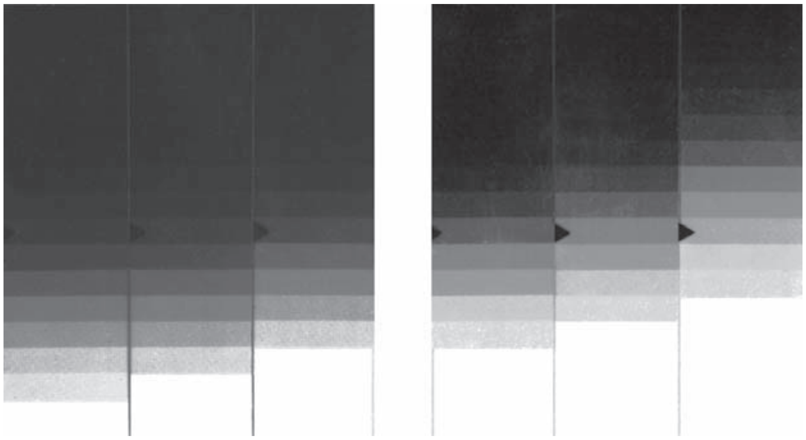


Figure 5-41 The three prints of a film step tablet on two different types of photographic paper all received the same photographic exposure but with decreasing illuminances and increasing exposure times from left to right. The decreasing densities with increasing exposure times are the result of reciprocity effects, with the paper on the right showing a more dramatic change.

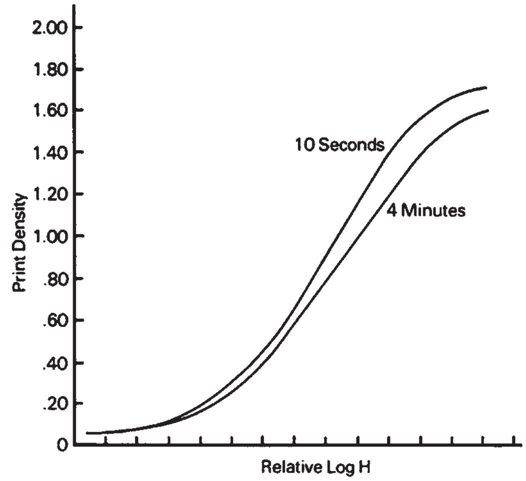


Figure 5-42 Excessively long printing times result in a decrease in paper contrast as well as speed. (The loss in paper speed has been adjusted to emphasize the loss in contrast.)

Reciprocity failure with some color materials can cause a change in color balance, as well as a loss in density.

decreased, the exposure time increased, and the development remained the same.

Noticeable reciprocity failure with printing papers is seldom encountered when using normal negatives. It is a problem, however, when printing a severely overexposed and/or overdeveloped negative to a large magnification. With the aperture wide open, the usual way to increase exposure is by lengthening print exposure time. Because of reciprocity failure, increasing print exposure times does not give the expected increase in image density.

Reciprocity failure also presents a problem when a high-density area in the negative has to be manipulated by burning-in or where high magnifications are required such as in printing photomurals or in printing small areas of a negative to a large print size.

In addition to a loss in speed with printing-paper reciprocity failure, one can also expect a loss in contrast. This is illustrated in Figure 5-42. The 240-second (4-minute) curve has been adjusted for the speed loss so that the loss in contrast is more apparent.

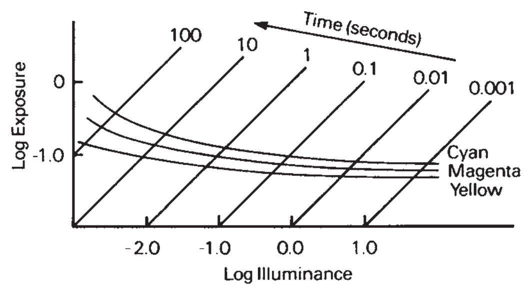


Figure 5-43 Reciprocity failure for a reversal color film. The reciprocity characteristics are made to match over a limited range of exposure times. Beyond those times the three different emulsions exhibit different degrees of reciprocity failure.

Whereas one can expect reciprocity failure to cause an increase in contrast for films exposed for relatively long times (low illuminances), a decrease in contrast for print papers can be expected.

Color Film Reciprocity

Figure 5-43 illustrates reciprocity failure curves for a color reversal film. The curves represent constant density lines for the cyan, magenta, and yellow dye layers of the film. Multilayer color films require the balancing of at least

three different emulsions so that their reciprocity failure characteristics, over an extended range of exposure times, are similar. For the color film represented in Figure 5-43, the reciprocity failure characteristics are similar over a range of exposure times between approximately 1/10 and 1/1,000 second. (This assumes that processing is in accordance with the manufacturer's recommendations.) When exposure times longer than 1/10 second are used, adjustments to the exposure given each of the three layers must be made. This is usually done by adding the proper color filter and increasing the exposure.

Film manufacturers have had considerable success in modifying reciprocity effects with alterations of the film and paper emulsions in recent years so that most contemporary films and papers suffer much smaller changes in image density, contrast, and color balance than films and papers produced previously.

Figure 5-44 The Sabattier effect (top). Note the partial reversal of tones and the black line along some of the contour.

Sabattier Effect

Photographic film or paper that is partially exposed to image-forming light and partially developed (but not fixed) can, if reexposed with uniform illumination, developed, and fixed, result in a partial reversal of tones. The reversal is most noticeable in the areas receiving the least exposure: the shadow areas for film and the highlight areas for paper. In addition to a partial reversal, the edge or contour of a shape is often strongly enhanced. This dark line effect, referred to as a Mackie line, and partial reversal of tones can be seen in Figure 5-44. To obtain the Sabattier effect, no special equipment or solutions of any kind are required:

1. Give the film or paper a somewhat less than normal image exposure.
2. Develop for about half the normal development time.
3. Rinse in water (do not use a stop-bath or fixing solution).
4. Reexpose by fogging to light for a brief time.
5. Return the film or paper to the developer and develop for the other half of the normal time.
6. Rinse, fix, wash, and dry as you normally would.

Note that for single sheets of film or paper, the rinse step can be eliminated. The second exposure can be made while the film or paper is in the developer. Allow the solution to settle for about 10 seconds, however, before making the second exposure.

Some experimentation may be required to get the desired results. The

Man Ray accidentally rediscovered the Sabattier effect and incorrectly labeled it solarization.

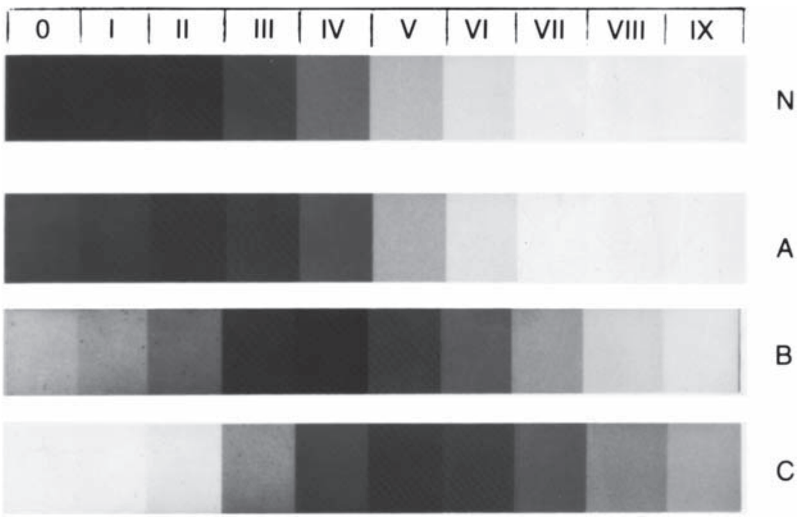


Figure 5-45 Gray scales showing the Sabattier effect. Gray-scale prints made from Kodak Super XX Pan Film processed for various combinations of first and second development times. (Films all received the same first and second exposures.)

Figure 5-46 An example of solarization caused by extreme overexposure of the sun. (Photograph by Leslie Stroebel).

ratios of first to second exposures and first to second developing times are important variables. Figure 5-45 shows that decreasing the first development time and increasing the second development time while keeping the fogging reexposure constant increases the amount of tone reversal.

Some modern films are difficult to solarize, especially if processed in a developer containing a silver-halide solvent.

Development Times

Gray Scale	1st Dev.	2nd Dev.	Total (minutes)
N	6	0	6
A	4	2	6
B	3	3	6
C	2	4	6

The Sabattier effect can appear if the fogging exposure is accidentally given during first development, as with unsafe "safelights." Applications of this effect have mainly been associated with interesting pictorial effects, but the line effect has been used, for example, to enhance the sharpness of spectrographic images. When the Sabattier effect is used with color negative or reversal materials, changes in hues, lightness, and saturation can be produced by varying the spectral energy distributions of the two exposures.[2]

Solarization

Increasing exposure increases density until a maximum density is reached. Extreme overexposure can result in a loss of density and reversal of the heavily exposed areas. Figure 5-46 shows a severely overexposed negative that resulted in a complete reversal of the sun. The degree of solarization depends on the particular film or paper and the developer used.

REVIEW QUESTIONS

1. In tone reproduction studies, the term *input data* refers to information about the . . .
   A. subject
   B. image

[2] Eastman Kodak Co., *Darkroom Expressions*, 1984, p. 64.

C. type of meter
D. exposure
E. film development

2. A subject has a highlight luminance of 200 c/sq.ft and a shadow luminance of 0.50 c/sq.ft. The luminance ratio of the scene is . . .

A. 20:1
B. 90:1
C. 150:1
D. 200:1
E. 400:1

3. A subject luminance ratio of 200:1 corresponds to a log luminance range of . . .

A. 1.3
B. 1.7
C. 1.9
D. 2.3
E. 3.0

4. Assume that a gray scale has been photographed, and the print made from the negative matches the original gray scale exactly. The tone reproduction curve for this situation would be . . .

A. a straight line
B. a C-shaped curve
C. an S-shaped curve

5. Using current international symbols, photographic exposure is defined as . . .

A. $E = I + T$
B. $E = I \times T$
C. $H = I \times T$
D. $H = E + T$
E. $H = E \times T$

6. Photographing a gray scale with a camera is not a completely satisfactory alternative to exposing film in a sensitometer because . . .

A. camera shutters tend to be inaccurate
B. camera flare affects image illuminances
C. light falls off toward the corners of the film
D. all of the above
E. none of the above. The camera is a satisfactory substitute for a sensitometer

7. The part of sensitometers that represents the subject is the . . .

A. light source
B. shutter
C. step tablet
D. filter
E. adjustable diaphragm

8. The most important reason for agitating film properly during development is to . . .

A. shorten the time of development
B. produce uniform development
C. keep the film wet
D. increase the effective film speed

9. If 80 units of light are incident on an area of a negative and 20 units are transmitted, the transmittance is . . .

A. 0.20
B. 0.25
C. 0.80
D. 2.50
E. 4.0

10. Density is defined as the . . .

A. antilog of the opacity
B. log of the transmittance
C. log of 1/opacity
D. antilog of the transmittance
E. log of the opacity

11. The density that corresponds to an opacity of 8 is . . .

A. 0.4
B. 0.6
C. 0.8
D. 0.9
E. 1.0

12. Most commercial densitometers are designed to measure . . .

A. specular density
B. diffuse density
C. doubly diffuse density

13. The maximum slope of film characteristic curves occurs in the . . .

A. toe region (only)
B. shoulder region (only)
C. straight line region (only)
D. straight line and shoulder regions
E. base-plus-fog region (only)

14. "Total negative contrast" is a synonym for . . .
    A. log exposure range
    B. luminance ratio
    C. curve slope
    D. density range
    E. D_{max} plus D_{min}

15. The useful log exposure range is the distance along the horizontal axis between the . . .
    A. two ends of the straight line
    B. two ends of the characteristic curve
    C. minimum and maximum useful points

16. Gamma is defined as . . .
    A. $(\Delta \text{ Log } H)/(\Delta D)$
    B. $(\Delta D)/(\Delta \text{ Log } H)$
    C. $(\Delta D) \times (\Delta \text{ Log } H)$
    D. $(\Delta D) + (\Delta \text{ Log } H)$

17. Gamma is considered to be a measure of . . .
    A. subject contrast
    B. negative contrast
    C. printing contrast
    D. development contrast
    E. exposure contrast

18. In the relationship SPEED = $1/H$, an appropriate unit for H is . . .
    A. footcandle
    B. second
    C. *f*-number
    D. lux-second
    E. meter-second

19. The lowest point on film curves where good shadow detail is retained is considered to be where the . . .
    A. log exposure is 0.1 above base plus fog
    B. slope is 0.1 above base plus fog
    C. density is 0.01 above base plus fog
    D. none of the above

20. The ISO (ASA) film speed for a film that requires .0064 lux-seconds' exposure to produce the specified density is . . .
    A. 100
    B. 125
    C. 160
    D. 200
    E. 400

21. For proper reproduction of the darkest detailed subject shadows in reflection prints, they should be located on the paper curve at a density of . . .
    A. 0.04 above base plus fog
    B. 0.10 above base plus fog
    C. 0.60 above base plus fog
    D. 90% of the maximum density
    E. the maximum density

22. The main difference between a number 1 grade paper and a number 4 grade paper is in the . . .
    A. range of log exposures they can accept
    B. minimum density obtainable
    C. maximum density obtainable
    D. location of the speed point on the curve

23. For printing with diffusion enlargers, the negative density range should . . .
    A. be 0.6
    B. be 0.85
    C. match the density range of the paper
    D. match the log exposure range of the paper
    E. match the contrast index of the paper

24. Enlarger flare light affects print contrast . . .
    A. more in the highlights than in the shadows
    B. more in the shadows than in the highlights
    C. uniformly in all areas

25. The exposure time range that produces minimum reciprocity failure with pictorial films is . . .
    A. 1 sec. to 60 sec
    B. 1/10 sec. to 1 sec
    C. 1/1000 sec. to 1/10 sec
    D. 1/100,000 sec. to 1/1000 sec

26. To obtain the correct density and contrast with films exposed for long exposure times at low illuminance levels, it is necessary to . . .
    A. increase the exposure and increase the development
    B. increase the exposure and decrease the development

C. decrease the exposure and increase the development
D. decrease the exposure and decrease the development
E. increase the exposure only

27. Mackie lines are associated with . . .

A. the Herschel effect
B. reciprocity effects
C. solarization
D. the Sabattier effect
E. the Mackintosh effect

28. Edge effects produce . . .

A. an increase in image sharpness
B. a decrease in image sharpness

29. The by-products of development act in a manner similar to the developer ingredient identified as the . . .

A. developing agent
B. activator
C. preservative
D. restrainer
E. solvent

30. The danger of film damage caused by static electricity is greater when the humidity is . . .

A. high
B. low

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chapter

6

Tone Reproduction

Photograph by Robert Weber, student, Rochester Institute of Technology

Purposes of Tone Reproduction

Except where the photographer is creating a photograph that bears no resemblance to an original subject, it is important to study the relationship between the tones in the original scene and the corresponding tones in the reproduction. Thus, by studying the factors influencing the reproduction of tone, the photographer can learn how to control the process to give the desired results.

Chapter 4 showed how the tone-recording properties of films and papers can be described through the use of the characteristic curve. If the conditions of measurement used to obtain the data simulate the conditions of use, the characteristic curve provides an excellent description of the tone-rendering properties of the film or paper emulsion. However, the result of the photographic process is a reproduction that will be observed by a person, which therefore involves the characteristics of the human visual system. In this respect, perceptual phenomena, including brightness adaptation, appear to play a significant role. Thus, determining the objective tone-reproduction properties required in a photograph of excellent quality is related to the perceptual conditions at work when the image is viewed. The final image that is viewed normally includes the cumulative tone-reproduction characteristics of the film or digital sensor plus the camera optics and the printing material plus the printing optics, inkjet, or laser printer characteristics or, in the case of slides and motion-picture films, the projector optical system.

Luminance is light per unit area, an objective concept. Lightness is a subjective perception that correlates only roughly with luminance.

The contrast of a photographic print will appear lower when viewed against a dark surround than when viewed with a light surround.

Objective and Subjective Tone Reproduction

When determining the tone-reproduction properties of the photographic system, objective and subjective aspects are considered. In the objective phase, measurements of light reflected from the subject are compared to measurements of light reflected or transmitted by the photographic reproduction or light emitted from a display. These reflected-light readings from the subject are called *luminances* and can be measured accurately with a photoelectric meter having a relative spectral response equivalent to that of the "average" human eye. The logarithms of these luminances are then plotted against the corresponding reflection or transmission densities in the photographic reproduction, and the resulting plot is identified as the objective tone-reproduction curve.

The perception of the lightness of a subject or image area corresponds roughly to its luminance but, unlike luminance, lightness is not directly measurable. Because the perception of lightness involves physiological as well as psychological factors, an area of constant luminance can appear to change in lightness for various reasons, including whether the viewer had previously been adapted to a high or a low light level. Psychological scaling procedures have been devised to determine the effect of viewing conditions on the perception of lightness and contrast. It has been established, for example, that a photograph appears lighter when viewed against a dark background than when viewed against a light background; and that the contrast of a photograph appears lower when viewed with a dark surround than when viewed with a light surround.

A graph showing the relationship between the perceived lightnesses of various areas of a scene or photograph and the measured luminances of the corresponding areas would be called a subjective tone-reproduction curve. It is because the perception of a photograph's tonal qualities can vary with the viewing conditions, that the American National Standards Institute and other organizations have prepared standards for the viewing conditions in which photographs are produced, judged, and displayed. The influence of viewing

conditions should not be underestimated when considering the specifications for optimum tone reproduction.

Objective Tone Reproduction/ Preferred Photographs

Most photographers realize that tone-reproduction characteristics required for satisfactory photographs depend to a great extent upon the lighting conditions under which the photographs are viewed. Unfortunately, reflection-type prints are commonly viewed under illumination levels ranging from less than 100 lux to more than 5,000 lux. (The Photographic Society of America currently recommends an illuminance of 800 lux for judging and displaying reflection prints [PSA Uniform Practice No. 1, 1981].) Large transparencies are usually viewed with back illumination, with a recommended illuminance of approximately 1,400 candelas per square foot.

However, since these transparencies are viewed under the same general room illumination as reflection-type prints, the eye is in a similar state of adaptation. Slides and motion-picture films projected onto a screen and observed in a darkened room are viewed with the eye in a considerably different state of adaptation. As there are three widely varying viewing conditions, different objective tone-reproduction curves are required if the photographs are to meet the subjective standards of excellence in each case.

In order to determine the objective tone-reproduction curve that gives the best subjective tone reproduction for black-and-white reflection prints, an experiment was performed under the conditions typically encountered by photographers. Various outdoor scenes were photographed at different exposure levels. The exposed films were processed to different contrasts, and from the resulting negatives black-and-white prints were produced. The prints varied in contrast, density, and tone-reproduction properties. Numerous observers were asked to view these prints and judge them for their subjective quality. The objective tone-reproduction curves for all of the first-choice prints were averaged, and the resulting curve is illustrated in Figure 6-1, where the reflection densities of the print are plotted against the log luminances of the scene.

The 45° reference line is arbitrarily located so that its lowest point corresponds to a diffuse white object in the scene and the minimum density of the photographic print material. If the luminances in the scene were reproduced exactly in the print, the resulting tone-reproduction curve would have a slope of 1.00, matching that of the reference line. In fact, the average curve for first-choice prints is located 0.2 to

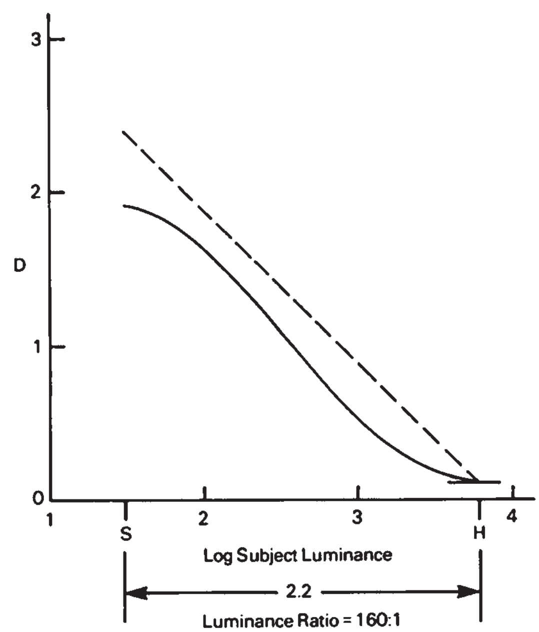


Figure 6-1 Objective tone-reproduction curve for a preferred reflection print of an average outdoor scene.

The tone-reproduction curve for facsimile reproduction would be a 45° straight line.

A projected image in a darkened room that had the same luminances as a good-quality reflection print would appear to be unacceptably flat.

0.3 density units below the 45° line except in the highlight region, where the curve cannot go below the minimum density of the paper. The curve shows low slope in both the highlight and shadow regions, but has a gradient of 1.1 to 1.2 in the midtone area. This indicates that the print's highlights and shadow regions are compressed compared to the original scene, while the mid-tones have been slightly expanded in contrast. The experiments that lead to this tone-reproduction curve involved scenes of low and high contrast, as well as interior and exterior subject matter. The results in all cases were remarkably similar to that shown in Figure 6-1. Whenever the departure from the desired slopes was greater than 0.05, the observers invariably judged the prints as being unacceptable in contrast, indicating very narrow tolerance levels. Consequently, it appears that the desired objective tone-reproduction properties in a black-and-white reflection print are essentially independent of the characteristics of the original subject.

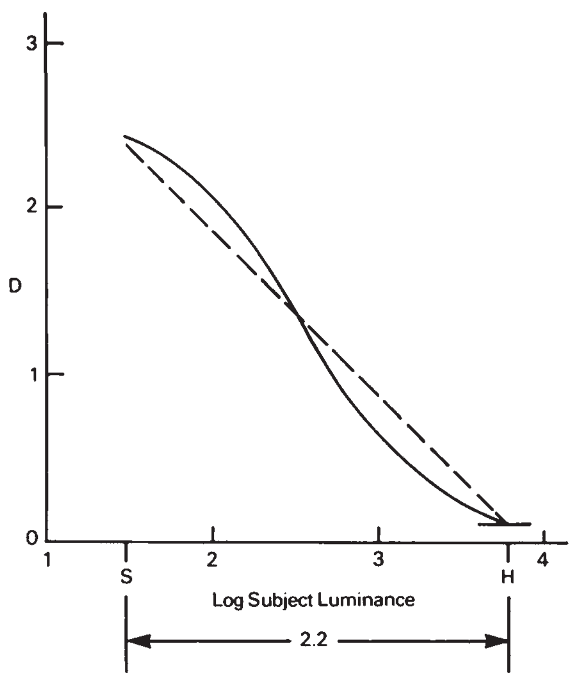


Figure 6-2 Objective tone-reproduction curve for a transparency of preferred quality, viewed on a bright illuminator under average room light.

Similar studies have been performed with large transparencies viewed under room light conditions on a back illuminator. The objective tone-reproduction curve that gave the best objective tone reproduction for this condition is illustrated in Figure 6-2, where the diffuse transmission density of the image is plotted against the log luminance of the scene. The desired objective tone-reproduction curve is very nearly the same as the 45° reference line but with a midtone slope still greater than 1.0.

The differences in curve shape between the transparency and the reflection print are due primarily to the increased density range of which the transparency film is capable, since the eye is in a similar state of adaptation. As the brightness of the illuminator used to view the transparency increases, the desired tone-reproduction curve moves slightly above and to the right of the one illustrated in Figure 6-2.

The preferred objective tone-reproduction curve for a transparency or a motion picture projected onto a screen and viewed in a darkened room is illustrated in Figure 6-3, where the effective screen viewing densities (measurements made with a spot photometer of the projected image on the screen) are plotted against the log luminances of the scene. This curve shows a slope considerably greater than that of the previous two and is principally the result of the dark-adaptation, lateral-adaptation, and visual-flare characteristics of the eye. Psychophysical experiments of the human eye's response indicate that the perceived brightness (lightness) contrast is lower when the eye is dark adapted than when it is light adapted.

Since it is desirable to obtain a subjective lightness contrast in the

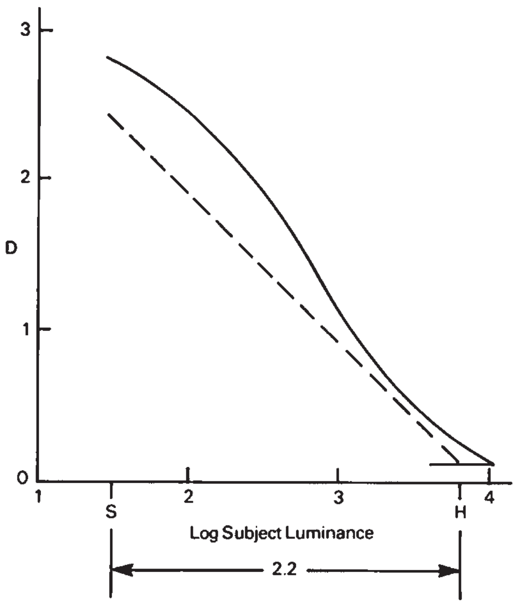


Figure 6-3 Objective tone-reproduction curve for motion pictures (and slides) of preferred quality, projected on a screen in a darkened room.

projected image on the screen similar to what would occur in a reflection print, the objective tone-reproduction curve necessary for dark-adapted conditions must have a greater slope. If a higher-intensity lamp is used in the projector, the tone-reproduction curve shifts slightly to the right and above that shown in Figure 6-3. Therefore, the preferred density level and optimum exposure for a transparency film are related to the amount of light supplied by the projector and screen used when viewing the images. This means that the effective film speed for a reversal film is in part related to the conditions under which the images will be viewed.

The three conditions illustrated represent those most commonly encountered in photographic reproductions and pertain only to pictorial representations. In each case, the (objective) curve represents optimum subjective tone reproduction, and thus an aim for the system. It is the task of the photographer to select the appropriate materials and processes to achieve these aims.

Objective Tone Reproduction Analysis

The flow diagram in Figure 6-4 isolates some of the more important factors to be considered in a study of the photographic reproduction of tones. Since the subject represents input in terms of log luminance values and the print represents output in terms of densities, it is the stages in between

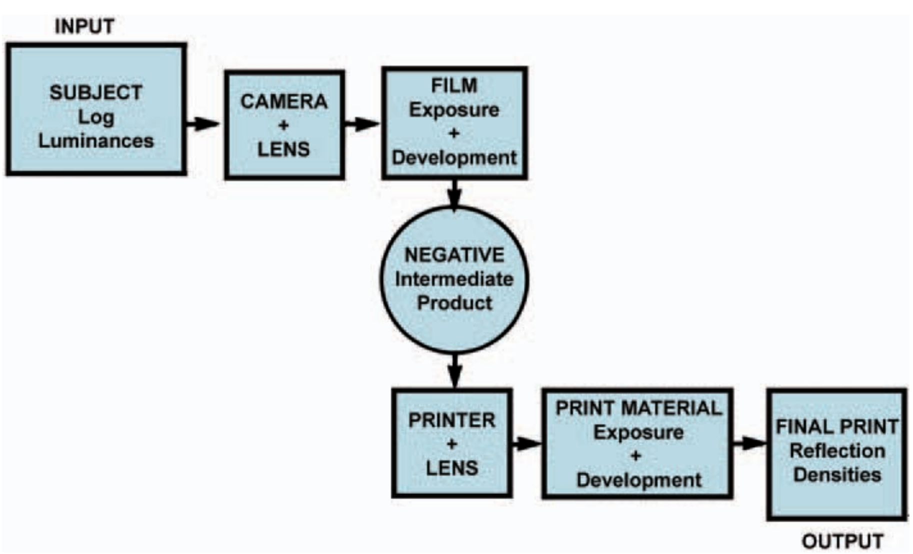


Figure 6-4 Flow diagram of the photographic process.

that must concern us. It should be noted that a study of tone-reproduction characteristics excludes many important properties of the photographic system. For example, no attention is paid to the reproduction of small detail or to the reproduction of various colors in the scene. Thus, when considering the various stages of the process, only those factors that influence the large-scale tonal relationship should be considered.

To simplify this task it is necessary to consider only three principal stages in the process, as illustrated in Figure 6-5. Each of these stages will be represented by a graph illustrating its influence on the tonal relationships. Each graph has a set of input values and a set of output values. The output from the first stage becomes the input to the second, and so on through the system, thus forming a chain of input/output relationships. In this fashion, the major stages of the process can be studied for their effects upon the end result. The important phases of the photographic process can be synthesized by means of this tone-reproduction study. For such an approach to work, data must be obtained about these phases. Methods for obtaining data about the subject, film, and photographic papers were discussed in Chapter 3 and so will not be repeated here. However, the problem of optical flare was only briefly mentioned in Chapter 2, and so a discussion of it follows.

Densities, which are used to measure image tones, are logarithms; therefore it is appropriate to express the measurements of subject tones as log luminances for tone-reproduction graphs.

Optical Flare

When a camera is aimed at a subject, the subject luminances and, therefore, the physical values of light reaching the lens represent the initial input data for the process. If the luminance of the lightest diffuse highlight is divided by the luminance of the darkest shadow with detail, the resulting value is termed the *luminance ratio*, and the log of that ratio is termed the *log luminance range*. In an important experiment conducted by Jones and Condit of the Eastman Kodak Research Laboratory, the luminance ratios of more than 100 outdoor scenes were measured. The frequency distribution of the luminance ratios is shown in Figure 6-6. The smallest ratio encountered was 27:1 and the largest was 760:1, with an average ratio of 160:1. The frequency distribution in Figure 6-6 indicates that luminance ratios of less than 100:1 and greater than 300:1 are encountered much less often.

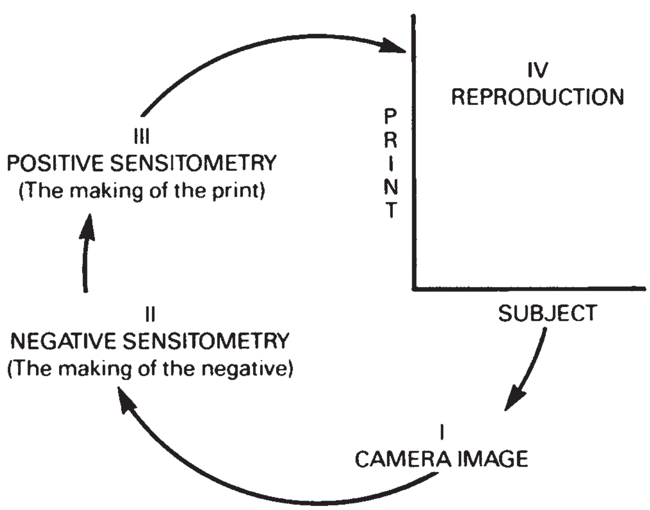


Figure 6-5 Simplified tone-reproduction system.

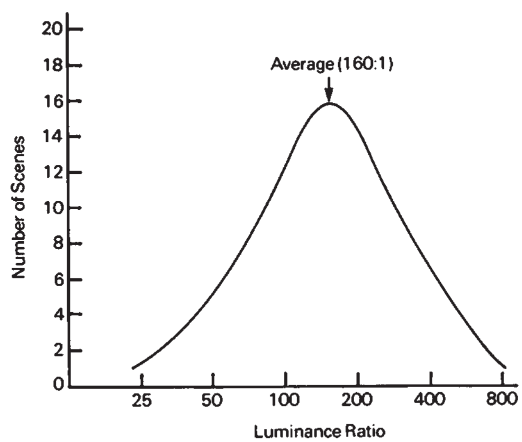


Figure 6-6 Frequency distribution of luminance ratios of outdoor scenes.

Much less information exists about the luminance ratios of interior scenes, but some experiments indicate that the average luminance ratio of an interior scene is not greatly different from 160:1. The average scene ratio of 160:1 has special significance since most manufacturers optimize exposure and development conditions for their products based on this value. A set of luminance readings from a typical outdoor scene is shown in Table 6-1. Nine different areas of the scene were measured with a spot meter to obtain the data. The luminance ratio of the scene is 160:1.

When the camera is pointed at such a scene, the lens receives the light from each area and focuses it on the film plane at the back of the camera. Thus, in this first stage of tone reproduction, the subject luminances are transformed to image illuminances at the image plane. In an ideal situation there would be a direct proportion between the subject luminances and the image illuminances and the tonal relationships would be maintained at the back of the camera. However, at any point in the image plane of a camera, the illuminance is the result of two different sources: (a) the illumination focused by the lens and projected to the image plane, which constitutes the image-forming light, and (b) light that is the result of single and multiple reflections from the lens surfaces, diaphragm, shutter blades, and additional interior surfaces of the camera, providing an approximately uniform illuminance over the whole image area.

This second source of light is referred to as *flare light*, or simply flare, and provides non-image-forming light, since it is not directly focused by the lens. Figure 6-7 illustrates how flare occurs in a simple camera. Flare light is present on any projected image, whether it is formed by the lens or a

The luminance ratio of average outdoor and indoor scenes is considered to be approximately 160:1.

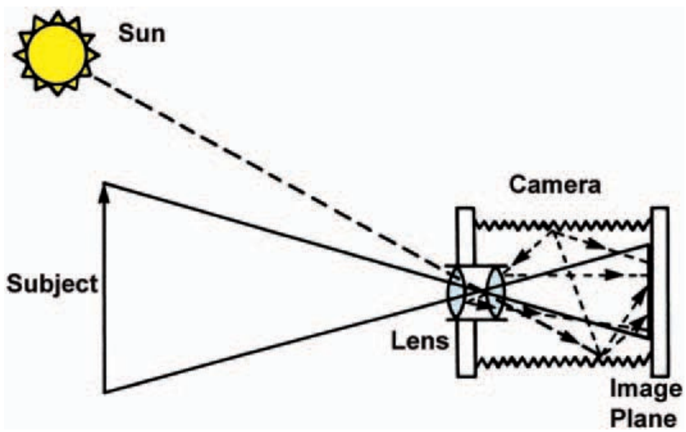


Figure 6-7 The occurrence of flare in a camera. Solid lines in camera represent image-forming light, while dashed lines in camera represent non-image-forming (flare) light.

Table 6-1 Luminance values of an outdoor scene

Area No.	Description of Area	Luminance Candela/Square Foot	Luminance Foot lambert
1	White cloud	1,114	3,500
2	Clear sky	637	2,000
3	Grass in sunlight	350	1,100
4	Side of house in sunlight	200	630
5	Front of house	115	360
6	Car in open shade	67	210
7	Tree trunk	38	120
8	Grass in shade	22	70
9	Base of tree in heavy shade	7	22

Luminance ratio of subject = 160:1

pinhole, because the projected light is reflected off any interior surface.

Since flare is non-image-forming light and occurs in the image plane as a uniform veil, it increases the illuminance of every point on the camera image and thus results in a loss of image contrast. The effect is similar to viewing a projected transparency on a screen in a darkened room and then viewing the same image with the room lights on. The loss of image contrast on the screen is due to the additional illuminance on the screen surface produced by the room lights.

To illustrate the effect in the camera, assume that the camera is being pointed at an average subject with a 160:1 luminance ratio. If there were no flare light in the camera, the range of image illuminances at the back of the camera would also be 160:1. However, if in addition to that image-forming light there was one unit of flare light uniformly distributed over the film plane (that is, the corners are receiving one unit, the edges are receiving one unit, the center is receiving one unit), the ratio would now be 161:2, which reduces to approximately 80:1. Thus the 160:1 luminance ratio in front of the camera has been reduced to an illuminance ratio of 80:1 at the back of the camera.

It is perhaps obvious that the reduction in contrast is the result of different percentage increases at the opposite ends of the scale. For example, the additional unit of flare light in the shadows provides a doubling of the light in that region, while the additional unit of light in the highlights represents only a very small percentage of increase in that region. The result is that the ratio of illuminances at the back of the camera is always less than the ratio of luminances in the subject. Flare can be expressed as a *flare factor* (Eq. 6-1), which is derived by dividing the luminance ratio in front of the camera by the illuminance ratio at the back of the camera:

$$\text{Flare factor} = \frac{\text{Subject luminance ratio}}{\text{Image illuminance ratio}} \tag{Eq. 6-1}$$

The flare factor will be 1.0 when there is no flare light, which would occur only in a contact-printing situation. The results of many experiments indicate that most modern lenses and cameras have an average flare factor of nearly 2.5 under typical conditions. Under some conditions, the flare factor may be as high as 4 or 8, or as low as 1.5.

Some of the more important factors that influence the amount of flare are:

1. *Subject characteristics*. Subjects with high luminance ratios or subjects with large areas of high luminance tend to produce large amounts of flare. Snow scenes, beach scenes, and high-key scenes (white on white) are all examples of subject matter that would give large amounts of flare.
2. *Lighting conditions*. Subjects that are backlit (with the light source in the field of view) give greater amounts of flare than subjects that are frontlit.
3. *Lens design*. Designing a lens to contain the smallest number of elements possible and coating the elements with antireflection materials will greatly minimize flare. However, lens design and coatings cannot decrease the flare factor to 1.00 (zero flare), since considerable stray light still reaches the image plane by reflection from the lens mount and other inner areas of the camera, and even the surface of the film itself.

4. *Camera design*. If the camera's interior is black and the surfaces are matte, stray light reflections will be minimized. Any light leaks in the camera body will also act as flare and further reduce the image contrast.
5. *Dust and dirt*. By keeping the lens surfaces clean and minimizing dust particles in the camera body, the number of surface areas on which light reflections may occur can be minimized and the flare reduced.

Of all the factors listed, the two with the greatest influence on flare are the subject characteristics and the lighting conditions. A number of studies suggest that approximately 80% of the flare encountered in typical photographic situations is governed by these two factors. Consequently, even when high-quality lenses and cameras are used and kept in good condition, the photographer cannot avoid the loss of image contrast that results from flare. Thus, it is important for the photographer to obtain an estimate of the amount of flare, in the form of a flare factor that is affecting the camera system.

The direct method for measuring flare involves the use of a gray scale and a small spot meter. The camera is focused on the gray scale and the small spot meter is used to measure the corresponding image areas at the back of the camera. The ratio of luminances on the original gray scale can then be compared to the ratio of illuminances at the back of the camera, and the flare factor can be computed. Although this method is direct, it is a difficult procedure to follow.

An alternative method for a film camera is to work backwards using a photographic film as the measuring device. First, a negative of the gray scale is made with the camera. A second piece of film is exposed in a sensitometer, which is a flare-free instrument since it involves a contact print. Both pieces of film are processed together to ensure identical development and the resulting characteristic curves are drawn. The highlight densities of the curves are matched, and any difference in the rest of the curves can be attributed to flare. The actual amount of flare can be found by measuring the horizontal displacements between the two curves, at the bottom of the top curve. The antilog of the difference in log exposures is the flare factor. There is currently no alternative method similar to this for a digital camera.

Such a set of curves is illustrated in Figure 6-8, which shows that the effect of flare on the characteristic curve is to increase the length of the toe, add curvature to the lower part of the straight line, and reduce the shadow contrast (slope) in the negative. The greater the amount of flare in the system, the greater the differences will be between these two curves.

The purpose for obtaining the flare factor is to estimate the range of illuminances that will occur at the back

Camera flare reduces contrast mostly in the shadow areas. Enlarger flare reduces contrast mostly in the highlight areas.

A typical camera flare factor of 2.5 reduces a scene luminance ratio of 160:1 to 64:1, and in small-format cameras it is a practical impossibility.

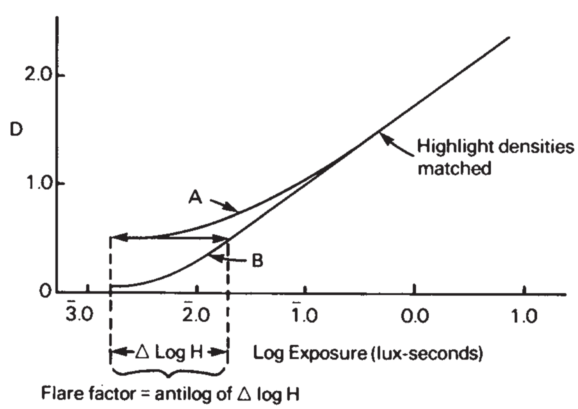


Figure 6-8 The effects of flare on the characteristic curve of a black-and-white negative material. Curve A was generated by photographing a reflection gray scale with a camera, while curve B came from a sensitometer (contact printed to a step tablet.)

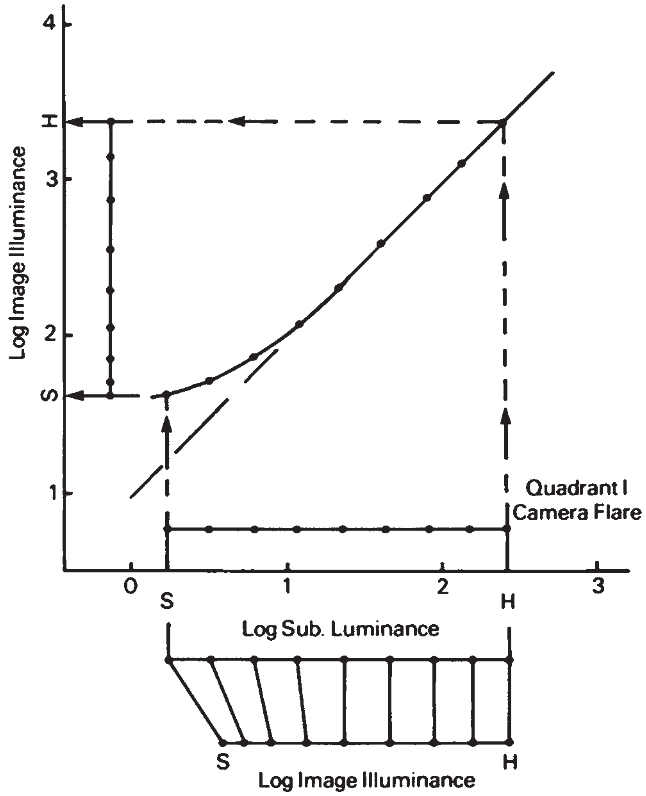


Figure 6-9 The effect of optical flare (or other stray light) on the image illuminances at the back of the camera.

of the camera, and thus the range of tones to which the film or sensor will be exposed. For example, if a scene with a luminance ratio of 200:1 is photographed with a lens-camera combination with a flare factor of 4, the film or sensor will actually receive a ratio of illuminances of 200 divided by 4, which equals 50:1. For film, the exposure ratio (or, more usefully, the log-exposure range) and ultimately the development time necessary to produce a normal-contrast negative, can be determined. In a digital system, the contrast would be adjusted using image editing software such as Photoshop. There are several options such as the Levels, Curves, or Contrast command that can be used.

In order to study more thoroughly the influence of flare in the tone-reproduction cycle, consider the graph in Figure 6-9. The data for such a graph are derived from the flare-measurement method first described. A small spot photometer was used to meter the illuminances provided by the gray scale at the back of a camera, and the relationships between subject luminance and image illuminance were plotted. Logarithms are commonly used to describe the input and output properties of light-sensitive photographic materials. For this reason the scales are log luminance and log illuminance on the graph. If there were no flare in the system, the relationship between subject log luminance and image log illuminance would be a 45° straight line, indicating a direct proportion.

However, as discussed earlier, the low-illuminance shadow regions at the back of the camera suffer a greater percentage increase than do the highlight illuminances. Since the highlights are relatively unaffected, the relationship is at a slope of 1.0 (45°) in that area. As the image illuminances decrease (the shadows become darker), the percentage increase becomes greater and thus reduces the slope of the curve considerably, resulting in a loss of contrast in the shadow area. This indicates that flare reduces shadow contrast in addition to reducing the overall ratio of tones at the film plane.

In Figure 6-9, the nine dots on the log luminance axis represent the nine luminances of a typical outdoor scene listed in Table 6-1. By extending straight lines directly up from these nine points until they intersect the flare curve, and then extending them to the left until they intersect the log illuminance axis, the nine dots on that axis can be generated.

A diagram at the bottom of Figure 6-9 compares the log subject luminances in front of the camera to the log image illuminances at the back of the camera for a normal amount of

camera flare. The log image illuminance range is shorter, indicating an overall loss of contrast, and the relationship between the darker tones has been compressed, indicating a loss primarily of shadow contrast.

The graph in Figure 6-9 is important because it represents the first stage of the objective tone-reproduction process and illustrates the effect on tonal relationships occurring at that stage. Ultimately, the log image illuminances will be fixed in position when the camera shutter is tripped, converting them to log exposures, which become the input to the film or sensor. In this example, the two dashed lines on the graph indicate the location of the darkest shadow with detail and the lightest diffuse highlight. These two tones will be followed through the four-quadrant objective tone-reproduction cycle.

The Making of the Negative

Tone reproduction will first be examined for a film-based system followed, later in the chapter, by a digital system.

The next stage of the process involves the making of the negative and is represented by the characteristic curve of the film-development combination used. Since the output of stage I (the optical flare quadrant) becomes the input of stage II (the making of the negative), it is necessary to rotate the characteristic curve of the film 90° counter-clockwise so that the log-illuminance axis of quadrant I matches the log-exposure axis for quadrant II, as illustrated in Figure 6-10. Here the broken line indicating the shadow detail area (*S*) has been located at the log exposure for the film that results in a minimum useful density of 0.10 above film base plus fog. This is reasonable as this density level is considered to be the minimum density for maintaining minimum shadow detail.

Since this is the ISO/ASA speed point for pictorial films, the shadow detail of the scene should be exposed in a way that produces this density. If less camera exposure is given, the dashed shadow detail line from quadrant I would intersect the negative curve at a much lower density (quadrant II would be shifted upward). If more

Flare in the human eye reduces contrast in the shadow areas, the same as flare in a camera does.

A negative density range of approximately 1.05 is recommended for printing on grade-2 paper with a diffusion enlarger, but a density range of 0.80 is recommended with a condenser enlarger.

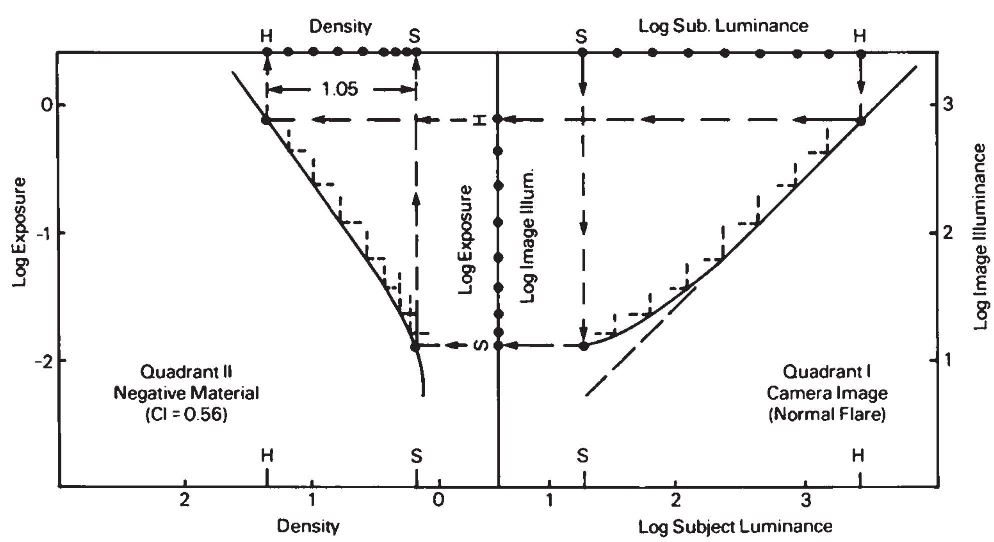


Figure 6-10 The combined effect of the transfer of camera flare onto the negative's characteristic curve.

camera exposure were given, the dashed shadow line would fall at a higher density on the characteristic curve (quadrant II would be shifted downward).

The shape of the characteristic curve shown in quadrant II indicates that it was developed to a contrast index of 0.56, resulting in a highlight density of 1.15 above base plus fog, as indicated by the dashed diffuse highlight line (*H*). The film was developed to this contrast index because it was desired to produce a negative with a density range of approximately 1.05, since it is known that such a negative will easily print on a grade 2 paper in a diffusion enlarger. If a condenser enlarger were to be used, the necessary range would be less, as discussed in Chapter 5. The nine dots on the density axis of the negative are generated by continuing the lines from quadrant I into quadrant II until they strike the characteristic curve, and then reflecting them upward until they intersect the density scale.

The relationship between the log exposures on the film and the resulting densities can be illustrated in a fashion similar to that of quadrant I, as shown in Figure 6-11. This diagram indicates that compression of tone is occurring at all levels in the image, with the greatest amount of compression occurring again with the shadow areas. This is typically the case for pictorial negative films, since they are invariably processed to contrast indexes less than 1.0. Thus, significant compression of tones occurs at the negative-making stage, with the darker shadow tones suffering the greatest amount of compression.

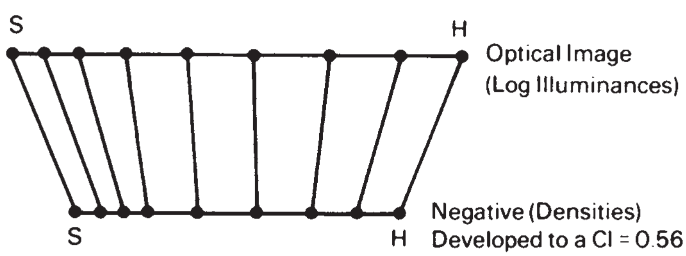


Figure 6-11 The relationship between the optical image at the film plane and the densities in the negative.

At this stage of the process, the photographer has many image controls available. Among the more important are:

1. *Film type*. To a great extent, the properties of the emulsion determine the shape of the characteristic curve. For example, lithographic (or lith) emulsions generally will produce curves with slopes greater than 1.0 under most development conditions, while pictorial films will produce slopes less than 1.0 under most development conditions. Therefore, if the input log exposure range is very short, the photographer would do well to select a lith-type emulsion. If, however, the log exposure range is long (1.3 or greater), a pictorial film would be a better choice. Specialized emulsions have been designed to handle log exposure ranges of excessive lengths (1,000,000:1 and greater).
2. *Development*. As discussed in Chapter 5, the length of development time provides a useful control for obtaining a variety of curve shapes (slopes) in the film. For pictorial applications, the concept of contrast index provides the most useful guide for estimating the required slope. The recommended development times found in most manufacturers' literature are those which will produce a contrast index of approximately 0.56, since this is the slope that will convert an average outdoor scene into a normal-contrast negative for diffusion enlargers. Flatter scenes will provide a shorter input range to the film and require a

steeper slope to maintain a constant density range (contrast) in the negative. Contrasty subjects will provide the film with a longer range of log exposures and consequently require a lower slope to maintain the density range at the normal level. Thus, development provides the photographer with a powerful tool for contrast control in tone reproduction.

3. *Exposure*. The task here is to select the appropriate *f*-number and shutter speed to place the shadow-detail area of the subject at an exposure that will produce the minimum useful density for shadow detail in the negative. If less exposure is given, less shadow detail will result. If more exposure is given, greater shadow detail will result. Thus the *f*-number and shutter speed selected will have the greatest influence upon reproduction of the shadow tones. It is important to note that underexposure by more than one-half stop introduces a compression of shadow tones that cannot be adequately compensated for in later stages of the process. On the other hand, with typical pictorial subjects and films, overexposure by as much as four stops can be compensated for in the later stages but with the result of increased print exposure and grainier prints.

The Making of the Positive

The third major stage of this system is the making of the positive. For the example that follows, the reproduction will be in the form of a reflection print. When printing a negative, the negative's densities control the exposures that the paper will receive. The thinner shadow areas of the negative will allow more light to strike the paper than will the denser highlight areas. Consequently, the output of the negative in the form of transmission densities can be related to the input of the photographic paper in the form of log exposures, which explains the positioning of quadrant III in Figure 6-12. Quadrant III represents the characteristic curve of a normal grade of black-and-white photographic paper.

The optimum contrast index for film development depends on scene contrast, type of enlarger, and paper contrast grade.

A print density of 0.04 above base density is considered appropriate for diffuse subject highlights, reserving paper white for images of light sources and specular reflections. The curve in quadrant IV of a tone reproduction diagram represents the relationship between the print tones and the subject tones.

The curve shape selected for this quadrant is based on the relationship between the density range of the negative and the useful log-exposure range of the paper. In Chapter 5, we saw that pictorial negatives generally are best printed on a paper in which the negative density range is equivalent to the paper's useful log exposure range. In this example, the negative has a density range of 1.05 and therefore requires a paper curve having a useful log-exposure range of 1.05, as does the curve in quadrant III of Figure 6-12.

The *f*-number and printing time of the negative determine the location of the characteristic curve in quadrant III relative to the left and right position. The best reproduction is generally obtained when the useful shadow density of the negative produces a density in the print equal to 90% of the maximum density of which the print material is capable, which is the basis for the location of the paper curve in quadrant III.

If the relationship between the negative and the paper is correct, the diffuse highlights of the negative should generate a density in the print that is approximately 0.04 greater than the

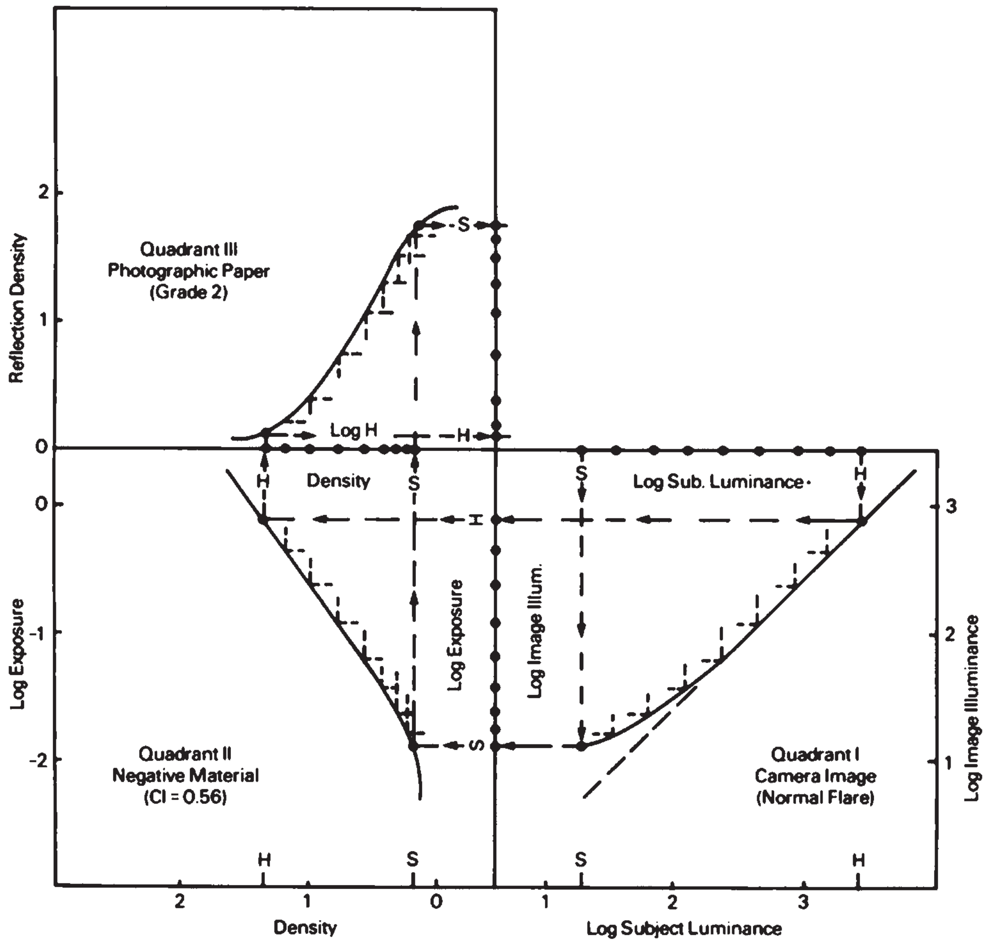


Figure 6-12 The combined effect of the transfer of camera flare through the negative characteristics and onto the print characteristics.

base density of the print. The broken shadow-detail line is extended upward from quadrant II, where it is reflected from the negative curve until it intersects with the print curve at its density of 90% of the maximum density.

Likewise, the dashed diffuse-highlight line is extended upward until it strikes the paper curve at the density equivalent to 0.04 above the base plus fog of the paper. Both lines are then reflected to the right, which is the way in which all of the dots on the print density line were generated. Figure 6-13 illustrates the relationship of the nine input tones to the paper (from the negative densities) and the nine output tones from the paper in the form of reflection densities. The midtones of the negative are expanded in the print, while the highlights of the negative are compressed.

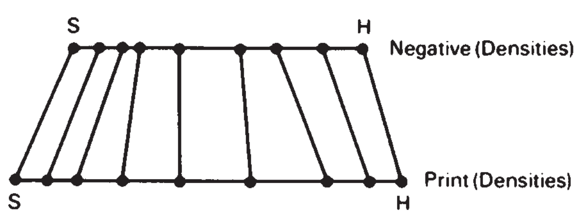


Figure 6-13 The relationship between the negative densities and print densities.

Generation of the Tone-Reproduction Curve

In the last phase of the system, the tones generated in the print are compared to the tones that existed in the original scene. As illustrated in Figure 6-14, this

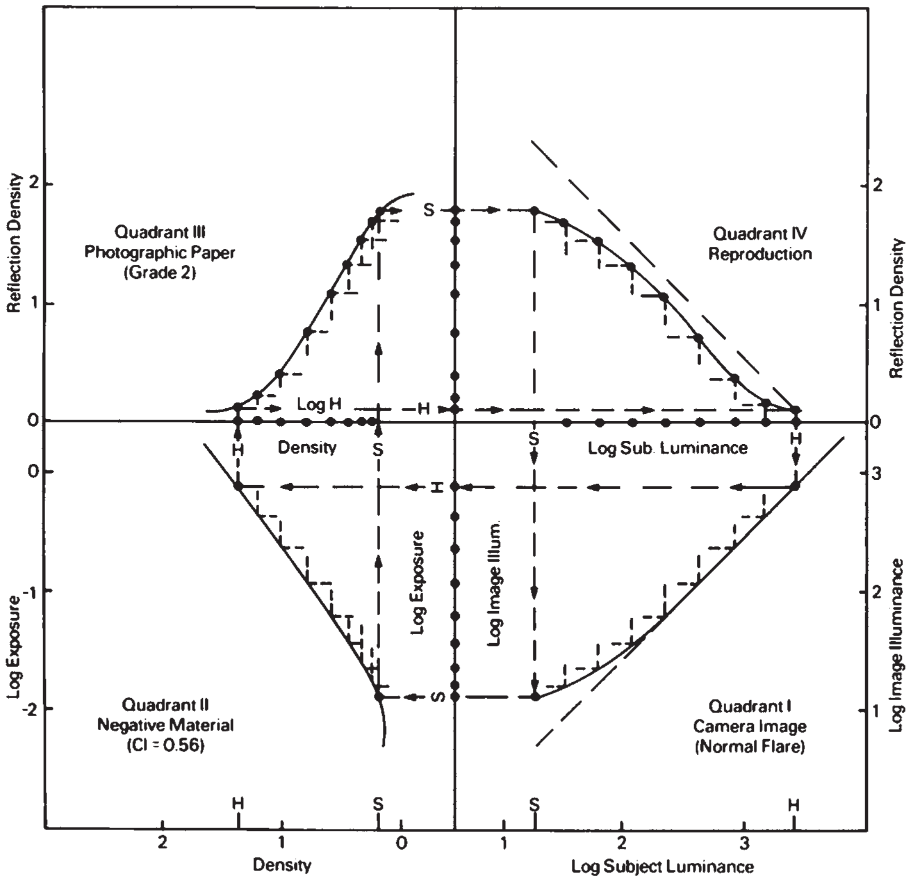


Figure 6-14 Complete objective tone-reproduction diagram for a pictorial system.

is achieved by extending the print tone lines from the photographic paper quadrant to the right into the fourth quadrant titled "Reproduction," and noting where they intersect the corresponding lines projected upward from the appropriate subject log luminances.

For example, in Figure 6-14 the line representing the diffuse highlight on the photographic paper curve has been extended into the fourth quadrant until it intersects the line extended upward from the diffuse highlight of the subject. The intersection of these highlight lines in quadrant IV determines the highlight point on the objective tone-reproduction curve. Likewise, the line representing the detailed shadow tone in the print is extended into the fourth quadrant until it intersects the line extended upward from the same tone in the subject, generating the shadow detail point of the tone-reproduction curve.

This procedure is repeated for each of the intermediate points to obtain the complete objective tone-reproduction curve in Figure 6-14 in the fourth quadrant. The shape of this curve can provide insight into the nature of the tone reproduction occurring in the photograph.

Alert readers will have noticed that a flare curve has not been included for the printing stage of the tone-reproduction process. All optical systems have flare, which, as we have seen with camera flare, can significantly affect image contrast. In this discussion of tone reproduction, it is assumed that contact prints are being made so that flare is not a factor at the printing stage. If prints are to be made with an enlarger, two additional factors must be

Color films scatter very little light and therefore have a Callier Q factor of approximately 1.0.

The four-quadrant tone-reproduction diagram reveals that for normal tone reproduction image contrast is reduced in quadrants I and II.

considered: flare and the Callier effect. Enlarger flare reduces contrast and the Callier effect increases contrast, but because the net effect of these two factors is different for diffusion and condenser enlargers, different data must be used for the two types of enlargers. The easiest way to incorporate this information into the four-quadrant tone reproduction system is to make the *D*-log *H* paper curves by projection-printing a step tablet with the type of enlarger that is to be used for future printing, being careful to mask the negative carrier down to the edges of the step tablet.[1]

In this idealized case, since correct exposure and development of the negative were achieved and the negative was correctly printed, the resulting tone-reproduction curve closely resembles that of the desired tone-reproduction curve for black-and-white reflection prints, illustrated in Figure 6-1. The 45° dashed line representing facsimile reproduction has been included in quadrant IV for comparison purposes only. Examination of the curve in quadrant IV reveals that the shadow region of the curve has a slope less than 1.0 (45°), indicating that the subject tones in the print have been compressed relative to those in the scene. This is also the case with the highlight region of the curve. In the midtone region, the slope is slightly greater than 1.0 (45°), indicating a slight expansion of midtone contrast in the print compared to the original scene.

Thus, in preferred tone reproduction for black-and-white reflection prints, there is often compression of shadow and highlight detail with an accompanying slight increase in midtone contrast. This relationship between tones in the photographic print and the tones in the original scene can also be illustrated as shown in Figure 6-15. In this representation, the nine different subject tones are equally spaced, indicating equal tonal differences. However, in the bar representing the print tones, the highlight and shadow tones have been significantly compressed, while the midtones have been slightly expanded. Again, this is typical of the negative-positive process when a reflection print is the final product.

At this point, it is useful to review the properties of the four-quadrant tone-reproduction diagram illustrated in Figure 6-14. This system represents a graphical model of the actual photographic process with respect to the reproduction of tone. The major limitations and strengths of the photographic system can be determined by such a diagram. For example, quadrant I represents the camera image as primarily affected by optical flare. Optical flare is an inescapable part of any photographic system that incorporates the projected image. Thus, the photographer must live with the compression of tone (loss of detail and contrast) that results from this problem. Little control can be exerted on the process at this stage except to use a lens shade and keep the lens clean.

Quadrant II represents the results of exposing and processing the film, and thus the production of the negative. At this point, the photographer can exert the greatest amount of

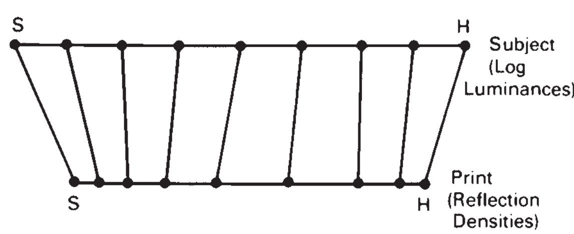


Figure 6-15 The relationship between the subject tones and the print tones.

[1] Leslie Stroebel, "Print Contrast as Affected by Flare and Scattered Light." *PSA Journal*, 48:3 (March 1982), pp. 39–42.

control through the selection of the film type and the corresponding exposure and development conditions.

Quadrant III represents the making of the print and, consequently, is the last step in controlling print tones. The choice of paper grade is primarily dictated by the nature of the negative because development variation does not have any significant effect on paper contrast. The photographer has only limited control of the outcome at this stage of the process. Additionally, if a reflection print is being made, the photographer must accept the fact that the print's tonal range will be less than that of the original subject.

The use of the four-quadrant tone-reproduction diagram also allows the photographer to see the expansion and compression of tones resulting at each stage of the process. For example, there is an inevitable loss of shadow contrast in the camera image caused by optical flare. Shadow contrast is further decreased when the shadow exposures are placed in the toe of the film's characteristic curve, which is typically the case. A third reduction in shadow contrast occurs when the negative is printed and the shadow tones of the negative are placed on the shoulder of the paper's characteristic curve. This explains the lowered contrast in the shadows of the final black-and-white reflection print.

The subject's midtones are relatively unaffected by the camera's flare characteristics and are typically exposed onto the straight-line section of the film's characteristic curve. Although the midtone slope of the negative curve is usually less than 1.0 (0.5 to 0.6), the midtones of the negative are printed onto the mid-section of the paper's characteristic curve where the slopes are considerably greater than 1.0 (1.5–3.0). The result is a mid-tone contrast in the print that is only slightly greater than that of the original subject.

The highlights are also unaffected by optical flare at the camera stage and, when the film is exposed, are placed on the upper straight-line section of the characteristic curve. Thus, the only distortion introduced into the highlights when the negative is made is associated with the lowered slope in the negative's characteristic curve. However, when the negative is printed, the highlight tones are placed in the toe section of the characteristic curve for the photographic paper and, as a result, suffer their greatest compression. This is the cause of the lowered slope and lessening of highlight detail in the tone-reproduction curve in quadrant IV.

It should be evident that all four quadrants can be described in terms of the slopes in the various areas (shadows, midtones, highlights) in each quadrant. Slope can be considered to be the rate of output for a given input, and the cumulative effect can be predicted by multiplying the slope of the curve in quadrant I by the slope of quadrant II, by the slope in quadrant III, to predict the slope that would result in quadrant IV. If the concept of the average gradient ($\bar{G}$) is substituted for slope, the relationship may be expressed by the following formula:

$$\bar{G}_{\mathrm{I}} \times \bar{G}_{\mathrm{II}} \times \bar{G}_{\mathrm{III}} = \bar{G}_{\mathrm{IV}} \qquad \text{(Eq. 6-2)}$$

The average gradient in each quadrant represents the average slope between the diffuse highlight point and the shadow detail point. For example, in Figure 6-14 the average gradient for quadrant I is 0.82, for quadrant II it is 0.56, and for quadrant III it is approximately 1.78. Substituting these values in the above formula gives the following result:

The average gradient of tone-reproduction curve is the slope of a straight line connecting the highlight and shadow points on the curve.

$$0.82 \times 0.56 \times 1.78 = 0.82$$

The calculations indicate that the average gradient for quadrant IV will be approximately 0.82, which is the case when the average gradient in quadrant IV is measured. A similar study may be done individually for the shadows, midtones, and highlights to assess the effect of each stage of the process on these areas. Often, this relationship between gradients can be used to work backwards in the system to predict the necessary gradient in any quadrant. For example, if it is desired to obtain an average gradient of 0.82 in quadrant IV (the reproduction quadrant), and it is known that a photographic paper with an average gradient of 2.0 will be used when making the print, and it is further known that the average gradient in the flare quadrant will be 0.82, the values can be substituted in the formula and the average gradient necessary in quadrant II can be predicted as follows:

$$0.82 \times \bar{G}_{\mathrm{II}} \times 2.0 = 0.82$$

$$\bar{G}_{\mathrm{II}} = 0.50$$

In this fashion, the photographer can predict the necessary contrast index for the production of an excellent print under these conditions. By knowing the relationship between contrast index and development time, the photographer can actually determine the proper length of development time for any set of conditions. The concept of relating the various stages of the photographic process through the gradient at each stage often serves as the basis for some very useful nomographs that assist the photographer in predicting such things as the correct development time for the negative and the proper printing conditions of the resulting negative.

It should be evident that these nomographs represent abstractions or simplifications of the objective tone-reproduction diagrams discussed in this chapter and, as such, are more useful to the photographer. However, it is important to have an understanding of the input-output relationships at the various stages of the process and the rates affecting those stages—that understanding is most directly obtained through an understanding of the four-quadrant tone-reproduction diagram.

Tone Reproduction for a Digital System

There are obvious differences between tone reproduction between a film system and a digital system. When studying a digital system it is necessary to have an understanding of the scene brightness characteristics, the response of the imaging sensor, the performance of the display that the image is viewed on, and lastly the behavior of the paper. The four-quadrant tone reproduction plot can still be used to study a digital system, however the quadrants now take on a different look.

In a digital tone reproduction study, quadrant I illustrates the tonal transfer between the subject log luminances and the resulting digital counts, often referred to as the detector response (see Figure 6-16). An image sensor, either CCD or CMOS, will typically have a more linear relationship to the subject luminances than to the log luminance. Therefore, quadrant I provides the same input-output relationship that a film system has, however, the output values are now digital counts.

Quadrant II represents the ability to alter the image characteristics after the image is captured. In a film-based system this quadrant is the film quadrant. Altering the processing of the film would control the output. For a digital tone reproduction study this quadrant can be thought of as representing the processing or altering of the digital

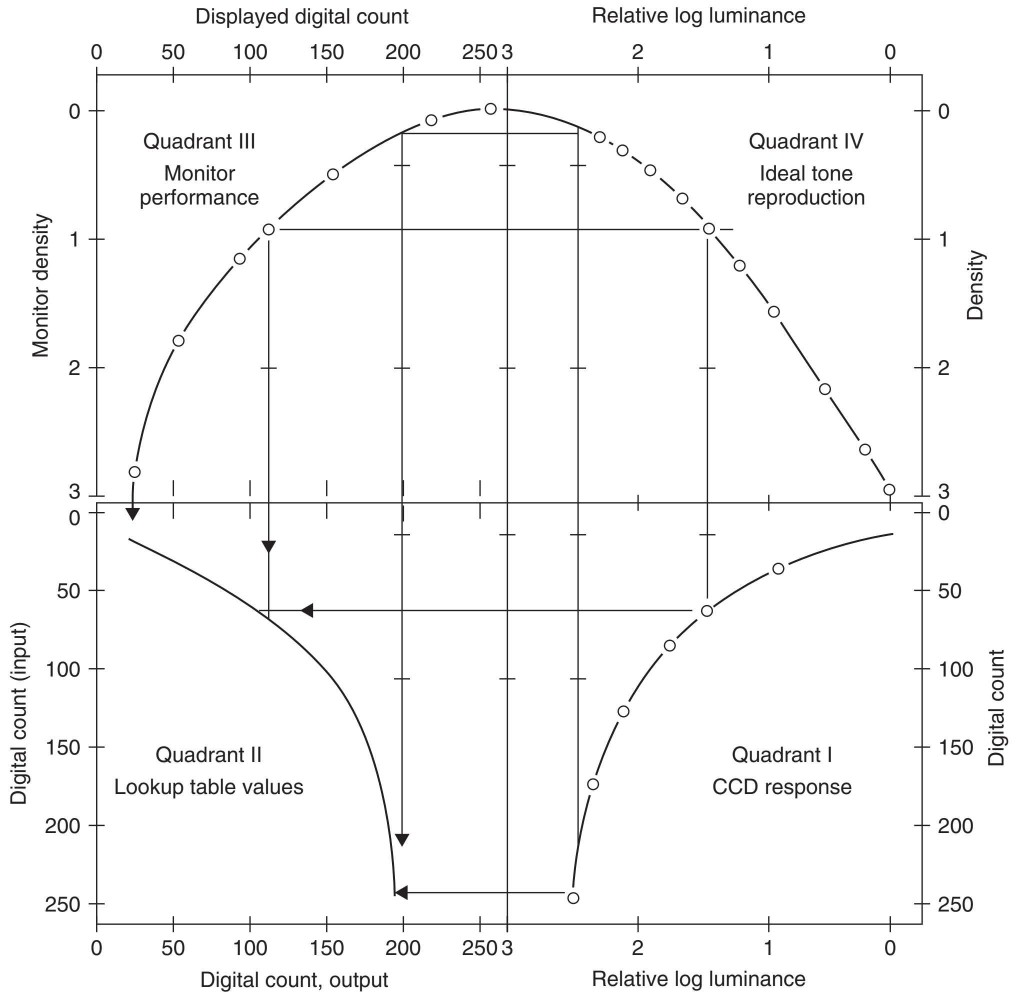


Figure 6-16 Four quadrant plot for a digital tone reproduction study.

image or data. In a digital system, there are many alterations that can be applied to the digital data, such as adjusting the contrast or color balance of the image or sharpening an image. Although these operations are done with complex math, all the operations can be combined into one look-up table or LUT. A LUT provides a new output digital value for each input digital count. Therefore, quadrant II is represented as a LUT to apply tonal alterations. If no modifications to the image take place, this would be a straight line with the input digital count value equal to the output digital count value.

In most digital applications, an image is first viewed on a display device such as a CRT or LCD monitor prior to printing. In some applications, this is where the tone reproduction study might end as a final print may not be required. Quadrant III illustrates the characteristics of that display device. The input is digital count that resulted from the results of the LUT applied in quadrant II. The output is monitor density. Monitor density is defined in Equation 6-3.

$$\text{Monitor density} = \left(\frac{\text{(Luminance for digital count} = 255\text{)}}{\text{Luminance for displayed digital count}} \right) \qquad \text{(Eq. 6-3)}$$

Several factors can affect this quadrant and the measurement of the luminance on the display. The settings for brightness and contrast will affect these readings. The recommendation is that these values should be set so as to provide the best linear relationship achievable between the display digital count and the screen density.

Quadrant IV provides the relationship between the final print that would be made from the image on the screen and the original scene luminances. The final print densities would be obtained using a reflection densitometer.

Tone Reproduction and the Zone System

The origins of the Zone System can be traced to the work done by engineers with light meters at the Weston Electrical Instrument Corporation in 1939.

"Without visualization the Zone System is just a five-finger exercise."—Ansel Adams

"One can choose to place any one luminance value on or in any one zone, but what governs the choice in the first place?"—Minor White

Ansel Adams lists the Zone Ranges as: 0 to X = full black to pure white, I to IX = dynamic range, II to VIII = textural range.

The concepts of tone reproduction and the accompanying tone-reproduction diagrams are intended to provide the photographer with a basis for understanding the nature of the photographic process. Experience has shown that photographers who have a firm understanding of the materials and how to control them are those most likely to consistently produce high-quality images. However, it is recognized that the tone-reproduction diagrams presented in this chapter do not provide a convenient way for photographers to exert control over the process at the time images are being made.

During the past several decades, there have been countless procedures proposed for the control of image quality through the manipulation of the various stages of the photographic process. For example, the early Weston exposure meter dial had U and O positions marked to represent shadow and highlight positions for a normal scene. A third position labeled N represented the average midtone position, and therefore the normal exposure. The U position was located four stops below the normal arrow, the O position three stops above the normal arrow. The difference between the U and O locations corresponded to a seven-stop range or a luminance ratio of 128:1 (or 160:1 rounded to the nearest whole stop).

Perhaps the most comprehensive system—certainly the best known—is the Zone System, which was proposed by Ansel Adams and further refined by Minor White and others. In its most elementary state, the Zone System provides the photographer with a vocabulary for describing the various stages of the photographic process from the original scene through the completion of the final print. In its more advanced form the Zone System will lead the photographer to proper exposure, development, and printing conditions in order to reproduce the scene in a given fashion. Thus the basic premise of the Zone System is that the photographer must visualize the final print from the appearance of the original subject before taking the photograph. Through knowledge of the capabilities and limitations of the photographic system, the photographer can then manipulate its various components to achieve this visualized result.

In tone-reproduction studies of pictorial systems, the subject properties are expressed in terms of luminances (candelas per square foot) and log luminances. In the Zone System, the subject is described in terms of *subject values*, which relate to different subject luminances that are labeled by Roman numerals for easy identification. The values are related to each other by factors of two (one camera stop); Value II reflects twice as much light as Value I, Value III reflects twice as much light as Value II and four times as much light as Value I, and so on.

Table 6-2 contains the 10 subject values commonly used in the Zone System and their definitions. Using these

Table 6-2 The relationship between various parts of a scene and the corresponding subject value in the Zone System

Subject Value	Description
0	Absolute darkest part of a scene. Example: when photographing the side of a cliff containing a cave.
I	A very dark portion of the scene where the surface of an object can be detected. Examples: dark cloth in shade; surface is visible with slight texture.
II	A dark area of the scene showing strong surface texture; perceptible detail. Examples: surface of building in heavy shade; shadow of tree cast on grass in sunlight.
III	Darkest part of scene where tonal separation can be seen; texture and shape of objects are evident. Example: tree trunk in shade where texture of bark and roundness of trunk with shading are evident.
IV	The darker midtones of a scene; objects in open shade. Example: landscape detail in open shade; dark foliage; Caucasian skin in shadow.
V	The middle gray tone of the scene; 18% reflectance. Examples: dark skin; gray stone (slate); clear north sky.
VI	The lighter midtones of a scene. Examples: average Caucasian skin in direct light; shadows on snow in sunlit scene.
VII	A very light area of the scene containing texture and detail. Examples: light skin in direct light; snow-covered objects with sidelighting.
VIII	The diffuse highlights (nonspecular) of the scene; white surfaces showing texture. Examples: white shirt in direct light; snow in open shade; highlights on Caucasian skin.
IX	The specular (glare) highlights of the scene; surface is visible but no texture. Examples: glare reflections from water, glass, and polished metal; fresh snow in direct sunlight.
X	The absolute brightest part of the scene. Example: a light source (sun, tungsten bulb, flash lamp, etc.) included in the field of view.

definitions, the contrast of the original subject can be described in terms of the number of values it contains. For example, the scene-luminance measurements by Jones and Condit that led to the average luminance ratio of 160:1 were made on the darkest and lightest areas of the scene. These areas most nearly correspond to Values I and VIII in the Zone System. This means that the typical outdoor scene contains eight values: I, II, III, IV, V, VI, VII, and VIII. Furthermore, since each value is related to the next by a factor of two (one camera stop), such a scene contains a seven-value range (VIII − I = VII), and the ratio of the extreme values can be found by multiplying 2 times itself 7 times (2^7). The resulting ratio of 128:1 compares closely with the results of the Jones and Condit study.

Thus, in Zone System terminology, the typical outdoor scene contains eight values and is said to cover a seven-stop range. If a scene contains fewer than eight values, it is a flatter-than-normal scene, while a scene with more than eight values would be described as a contrasty scene. It is important to note that many references describe the average outdoor scene as containing five (or some other number) values ranging typically between Value III and Value VIII. The discrepancy is due to at least two factors. The first is associated with defining exactly what is meant by the terms *detailed shadow* and *textured highlight*. Obviously, the opinions of photographers will differ as a result of esthetic judgments. The second reason (and perhaps a more fundamental one) is related to the definition of a value. Some references define a value as an interval—a difference between two tones—while others state that it is a specific tone or subject luminance. This problem will cause a one-value discrepancy, since the number of intervals

F-numbers are positions on a scale while *f*-stops are the intervals between positions.

The Zone System Personal Speed Index is based on a negative density of 0.10 above base-plus-fog density for Zone I.

In the late 1800s, the photographer Dr. P. H. Emerson put this question to Hurter and Driffield, the fathers of photographic sensitometry: "Suppose I want to photograph three houses, a white one, a gray one, and a black one. What is it you say I have to do to secure a truthful rendering of tone; what is it you say I can alter by development, and what is it I cannot alter?"

between tones will always be one less than the number of tones. In all discussions of the Zone System in this text, a value is defined as a specific tone and the difference between tones as a value range. The difference between tones is also expressed as a stop range, log luminance range, and luminance ratio.

The value range of a subject can be converted to a log luminance range by simply multiplying the number of camera stops (factors of two) it contains by 0.30, the log value of one stop. Thus the average outdoor scene containing eight values covers a seven-stop range, which will give a log luminance range of 2.1 ($7 \times 0.3 = 2.1$) and a luminance ratio of 128:1. A flat scene containing only five values covers a four-stop range and gives a log subject luminance range of 1.2 ($4 \times 0.3 = 1.2$) or a ratio of 16:1. A contrasty scene containing nine values will cover an eight-stop range and give a log range of 2.4 ($8 \times 0.3 = 2.4$) or a ratio of 256:1. Therefore, in its initial application the Zone System provides the photographer with a method of describing and quantifying the tonal values of the original scene. In the more technical tone-reproduction system, this correlates with the determination of the subject luminance ratio and ultimately the log subject luminance range as the principal description of the subject contrast.

In its second phase, the Zone System provides a way to determine the proper exposure and film development to obtain a normal-contrast negative. However, as with all systems of image control, it is necessary to test the film extensively to determine its characteristics. In the Zone System this invariably involves determining the camera exposure necessary to obtain the details desired in a particular shadow value, and the development necessary to correctly reproduce a given highlight value. Typically, the photographer would arrive at a personal working film speed and would determine the relationship between development time and contrast in the negative.

In this context, the subject values are translated into exposure zones, which are described by a similar set of Roman numerals. Although subject values can be measured in candelas per square foot (c/ft^2), they are typically determined through visual (subjective) evaluation of the scene. Exposure zones (or, more simply, zones) are used to describe the input exposure scale of the film and are more technical. Thus a given subject value may be placed in any exposure zone, with the other values falling on the exposure scale where they may. Typically, an area of important shadow detail is placed in a lower exposure zone (Zone II or III), with the higher values (highlights) falling in higher zones, depending upon their lightness.

In Zone System terminology, the development time necessary to make a typical outdoor scene (eight values) results in a negative of normal contrast (density range equal to 1.10 for printing with a diffusion enlarger) is identified as "N" development. The development time necessary to make a nine-value subject result in a normal-contrast negative (density range of 1.10) is defined as "N minus one zone," or simply, "N minus 1." Similarly, a subject containing only six values would require N plus 2 development to yield a normal-contrast negative.

The concept of zone development is related to the use of a normal contrast index for film development. "N minus" development is associated with lower-than-normal contrast-index values, while "N plus" development is associated with higher-than-normal contrast indexes. In the Zone System, "N plus" development is often referred to as expansion, while "N minus" development is referred to as compaction (see Table 6-3).

Table 6-3 Development index for Zone System

Development Index for Zone System	Contrast Index	
	Diffusion	Condenser
N + 2	0.72	0.55
N + 1	0.63	0.47
N	0.56	0.42
N − 1	0.53	0.39
N − 2	0.50	0.37

Therefore, the function of the Zone System at this stage is to assist the photographer in placing the important shadow value at some minimum useful position (Exposure Zone II or III) in the toe of the characteristic curve, and to provide the proper development that will result in a normal-contrast negative, regardless of the original scene contrast. This phase of the Zone System is often summarized by the following statement: "Expose the film for the shadows and develop the negative for the highlights." If the photographer has provided correct exposure and development, the density values produced in the negative will just fill the reproduction capacity (useful log exposure range) of a normal grade of photographic paper.

The third phase of the Zone System involves the printing of the negative and, therefore, the production of print values. At this stage, the concept of zones can, again, be used to describe the appearance of the tones of gray in the print; however, the term *print value* is used instead of *zone* to differentiate it from the exposure scale of the negative. Since reflection prints are limited in the range of tones that can be produced, and since there is distortion present in the photographic process, the values of the print have different definitions. These are listed in Table 6-4. The goal is to produce a print in which the values of the original subject are reproduced as the desired values in the finished print. This

Table 6-4 The relationship between the various reflection densities of the photographic paper and print values

Value	Description
0	Maximum density of paper; principally determined by surface characteristics of print; absolutely no tonal separation.
I	In theory, a just-noticeable difference from the maximum density. Sensitometric tests indicate that this value is located at 90% of the maximum density. At print densities higher than this, texture is suppressed.
II	Darkest area of the print where strong surface texture is still maintained. Approximately equal to a density that is 85% of the maximum density.
III	Darkest area of the print where detail can be seen; in the shoulder of the curve where there is sufficient slope for tonal separation.
IV	The darker midtones of the print. The upper midsection of the curve is used, giving obvious tonal separation.
V	The middle gray tone of the print; 18% reflectance; reflection density of 0.70. Occurs in the middle of the curve, producing maximum tonal separation.
VI	The lighter midtones of the print. The lower midsection of the curve is used where the slope is still quite high, yielding good tonal separation.
VII	A very light area of the print containing texture and detail. The toe section of the curve is employed where the slopes and densities are low, causing tonal compression.
VIII	The diffuse (nonspecular) highlights of the print. The just-noticeable density difference above the paper's base-plus-fog density. A reflection density of approximately 0.04 above base plus fog.
IX	The specular highlights of the print. This is the base-plus-fog density of the paper and is the absolute whitest tone obtainable in the print.
X	Base plus fog density of the paper; maximum white (same tone as print zone IX).

phase of the Zone System is analogous to the third quadrant of the tone-reproduction diagram, in which the characteristic curve of the photographic paper is inserted and the output expressed in terms of reflection densities.

At this point, the Zone System comes full cycle; the photographer views the final print and determines the closeness with which it matches the visualized print. The results of this evaluation provide the basis for future refinements and improvements of the system. At this stage, photographers rely upon their subjective opinion regarding the quality of the final image. However, the Zone System provides photographers with a vocabulary and a set of measurement concepts that can provide a clear understanding of the factors influencing the final result. In the objective tone-reproduction system, this relates closely to the fourth quadrant, which contains the tone-reproduction curve resulting from the combination of materials and processes used to make the photograph. In the tone-reproduction system the quality of the final print can be assessed in terms of how closely it matches the aim curve for that particular system. In the Zone System, the quality of the reproduction is assessed relative to what the photographer visualized in the subject.

"The Zone System is . . . a codification of the principles of sensitometry worked out by Fred Archer and myself around 1939–40."
—Ansel Adams

"What one selects as the important shadow is a matter of personal choice and a choice that must be made afresh for each photograph."
—Minor White

"Caucasian skin in sunlight is rendered with an amazing illusion of reality as a Print Value VI."
—Minor White

The similarities between the tone-reproduction system and the Zone System are not the result of chance. The Zone System actually represents a practical simplification of the concepts of tone reproduction. It is not surprising then, that many photographers have trouble understanding and implementing the Zone System without understanding the tone-reproduction system. The relationship between the two systems can be illustrated in a variety of ways. First, consider Figure 6-17, which represents an adaptation of Zone System terminology to the conventional four-quadrant tone-reproduction diagram. This figure reveals the distortions encountered by the original subject zones in their travels through the photographic process. Notice, for example, that the shadow values are compressed first because of the camera's flare characteristics, second because they are placed in the toe section of the film curve, and third because they are placed in the shoulder section of the paper curve.

As a result, the print's shadow values are considerably compressed compared to the shadow values in the subject. Although the highlight values in the subject are unaffected by camera flare, they are somewhat compressed by the minimum slope in the upper portion of the film curve, and greatly compressed as a result of being exposed onto the toe section of the paper curve. Thus the print's highlight values are greatly compressed compared to the highlight values of the original subject.

The midtone subject values are relatively unaffected by camera flare but they are somewhat reduced in contrast because of the medium slope (less than 1.0) in the mid-section of the film curve, and they are greatly expanded in contrast because they are placed in the steep mid-section of the paper curve. As a result of these conditions, the midtone values in the print are slightly expanded compared to the midtone values in the subject. Thus there is not a simple one-to-one relationship between the values of the subject and the values in the final print.

The effects of various stages of the photographic process on the subject values can also be illustrated through the use of a bar diagram as shown in Figure 6-18. The horizontal bar designated Subject Values has been divided into 10 equal values, with the appropriate Roman numerals. Value I and Value VIII have been marked to indicate

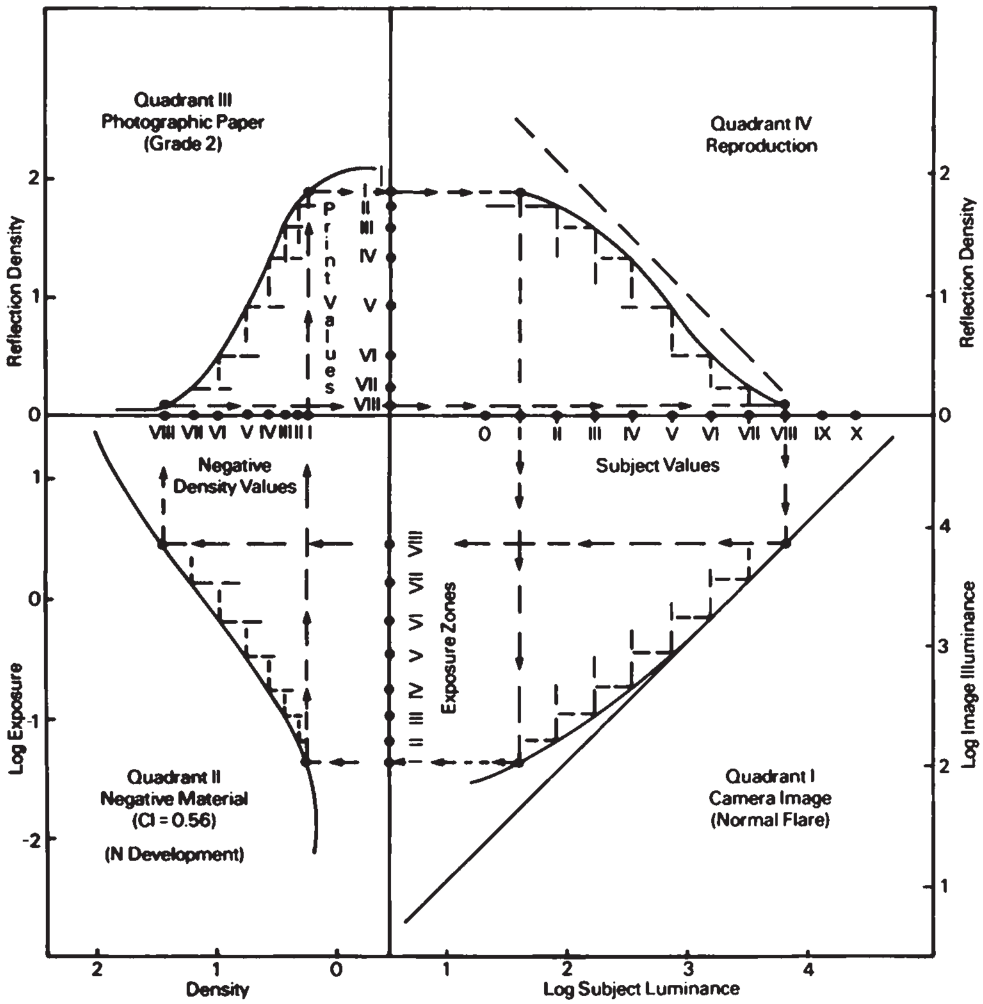


Figure 6-17 Objective tone-reproduction diagram illustrating the Zone System concept.

that they cover the range nearly equivalent to that of a typical outdoor subject. The Exposure Zones bar illustrates the effect of camera flare on the optical image at the back of the camera. Here only the lower (shadow) zones are being compressed.

A third bar represents the density values in the negative after it has been given "N" development (contrast index equal to 0.56). Notice that the shadow zones have been further compressed and now the midtone and highlight zones are compressed. The fourth bar illustrates the relationship of the print values for a glossy paper, assuming the negative was printed in a diffusion enlarger. The highlight values are considerably compressed compared to the corresponding zones in the original subject. The midtone values show a slight expansion, indicating they have a slightly higher contrast than the corresponding subject zones. Figures 6-17 and 6-18 are presented with the belief that an understanding of tone-reproduction principles will facilitate an understanding of the Zone System. In no way can such diagrams be substituted for the actual testing of the photographic system and for the creative use of the results. The four-quadrant tone-reproduction system, however, can be correlated with the Zone System provided the exposure meter and shutter are known to be accurate (or the errors are known and compensated for); and the flare, film, and paper curves are appropriate for the materials and equipment.

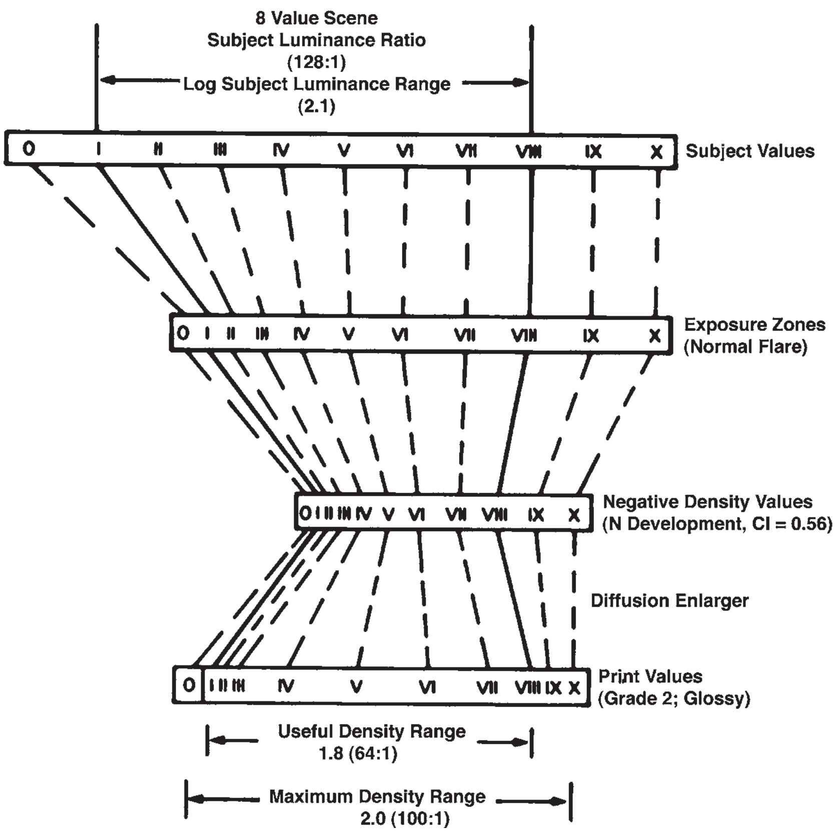


Figure 6-18 Distortion of zones that occurs at the major stages of the photographic process. (Adapted from Eastman Kodak Publication F-5.)

REVIEW QUESTIONS

1. One of two identical photographic prints is viewed in front of a white background and the other is viewed in front of a black background, with identical illumination on the two prints. The print in front of the white background will tend to be judged as being . . .

   A. lighter
   B. darker

2. The density of the center portion of the "preferred" tone-reproduction curve is . . .

   A. the same as the density of the corresponding subject area
   B. less than the density of the corresponding subject area
   C. more than the density of the corresponding subject area

3. If a scene luminance ratio is 150:1 and the image illuminance ratio at the film plane of a camera is 50:1, the flare factor is . . .

   A. 1
   B. 2
   C. 3
   D. 50
   E. 100

4. For normal exposure of the film, the shadow should be located on the curve in quadrant II where the . . .

   A. log exposure is 0.04 above the base-plus-fog log exposure
   B. log exposure is 0.1 above the base-plus-fog log exposure
   C. density is 0.04 above the base-plus-fog density
   D. density is 0.1 above the base-plus-fog density
   E. density is 90% of D_{max}

5. When selecting a grade of paper in quadrant III, the selection should be made so that the . . .

   A. density range of the paper matches the density range of the negative
   B. log exposure range of the paper matches the log exposure range of the negative
   C. density range of the paper matches the log exposure range of the negative
   D. log exposure range of the paper matches the density range of the negative

6. The curve in quadrant IV for a film system represents the . . .

   A. print
   B. relationship between the print and the negative
   C. relationship between the print and the subject
   D. relationship between the negative and the subject

7. In the Zone System, diffuse highlights are represented by a subject value of . . .

   A. VI
   B. VII
   C. VIII
   D. IX
   E. X

8. In the Zone System, "N minus 1" development is recommended for . . .

   A. a six-value subject
   B. a seven-value subject
   C. an eight-value subject
   D. a nine-value subject
   E. a ten-value subject

chapter

7 Micro-Image Evaluation

Bloom by Douglas Gaston IV, Biomedical Photographic Communications student, Rochester Institute of Technology

Image Characteristics

The small-scale image characteristics of *graininess*, *sharpness*, and *detail* (collectively called *definition*) strongly influence picture quality. A photographer can produce a print that has good tone-reproduction qualities but suffers in overall quality because of excessive graininess, lack of sharpness, or insufficient detail. For this reason, it is important to understand small-scale image characteristics and how they relate to the choice of photographic materials, equipment, and processes. The micro-image attributes of sharpness and detail apply to the optical image formed

Graininess is a subjective property. Granularity is an objective property.

by a lens as well as the photographic image recorded on light-sensitive film or paper. Graininess, however, is a characteristic imposed on the image by the recording material.

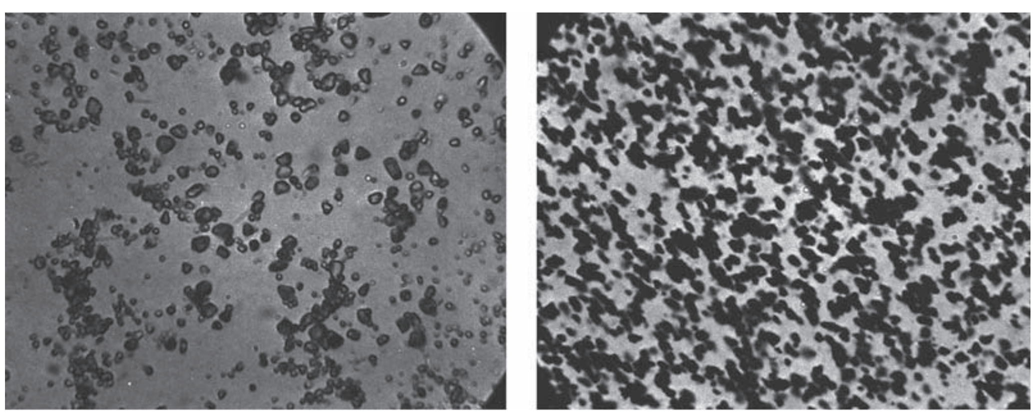
Graininess/Granularity

Photographic emulsions consist of a dispersion of light-sensitive silver halides in a transparent medium such as gelatin. Figure 7-1 represents a small area of unexposed photographic film magnified 2,500 times. Figure 7-1(A) shows the emulsion in its pristine state, before exposure and development.

The crystals vary in shape and size, and crystals with similar shapes can be oriented in any direction within the thickness of the emulsion. The spacing between the crystals varies, with some crystals touching and others overlapping. Although the crystal size typically varies widely within a given emulsion, the average size is generally larger in fast films than in slow films. It should be noted, however, that the size of the silver halide crystals is not the sole determinant of film speed.

The exposed silver halide crystals are transformed during development into grains of silver that are more or less opaque, depending upon their size and structure (see Figure 7-1(B)). The developed silver grains seldom conform exactly to the shapes of the silver halide crystals. The size and shape of each silver grain depends upon the combination of exposure, developer type, and degree of development in addition to the size and shape of the original silver halide crystal. As the silver grains increase in size, the spaces between the grains through which light can pass freely become smaller. The overlap in depth of the individual silver grains results in a rather haphazard arrangement of silver grain clusters. This nonhomogeneity of the negative image usually can be detected in prints made at high magnifications as an irregular pattern of tonal variation superimposed on the picture image. Figure 7-2(A) compares enlarged prints and transparencies made from different 35-mm films. Notice the loss of fine detail as graininess increases.

Graininess is an important variable since it sets an esthetic limit on the degree of enlargement, as well as a limit on the amount of information or detail that can be recorded in a given area of the film. Graininess can be thought of as noise or unwanted output that competes with the desired signal (the image). All recording mediums



A B

Figure 7-1 Silver halide crystals. (A) Grains of silver halide are randomly distributed in the emulsion when it is made. (B) Silver is developed at the sites occupied by the exposed silver halide.

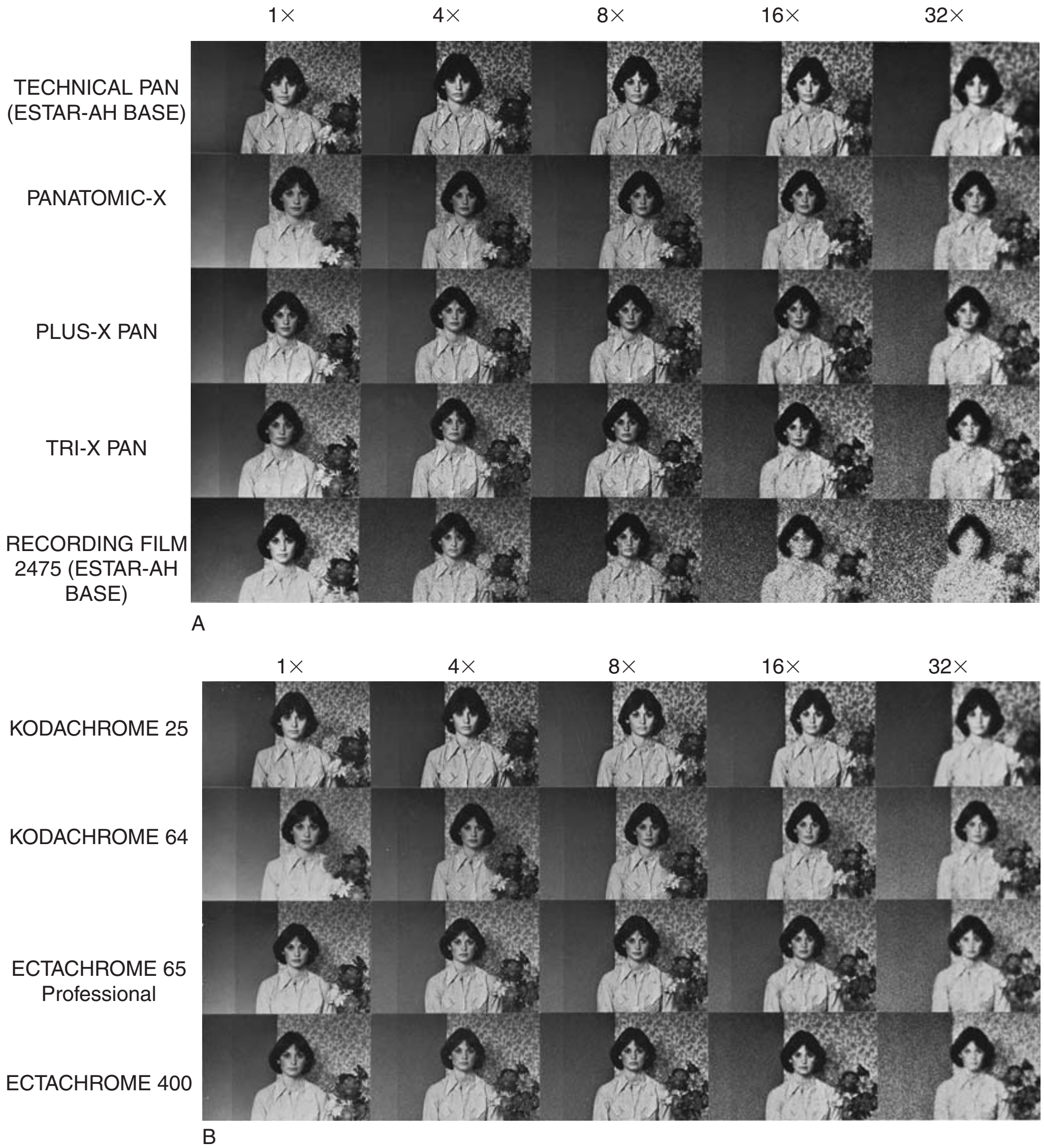


Figure 7-2 The effect of film graininess on detail. (© Eastman Kodak Company.) (A) Comparison prints from five different 35-mm black-and-white negatives at various magnifications. (A 32 × magnification represents a 30 × 45-inch print.) (B) Comparison of four different 35-mm color transparency films at various magnifications (1 ×, 4 ×, 8 ×, 16 ×, and 32 ×). (Continued on next page.)

have some type of noise that limits the faithfulness of the desired signals, including televisions, digital sensors, and video and audio tapes and discs. Graininess, which can be esthetically pleasing, adversely affects sharpness and resolution. Even though graininess, sharpness, and resolution are defined as three distinctly different image characteristics, in practice they are not entirely separate and independent.

Since graininess is generally considered to be an undesirable characteristic, why not make all photographic film fine-grained? Fine-grained film represents a trade-off in which some film speed has been sacrificed. There tends to be a high correlation between graininess and film speed, as shown in Table 7-1. It should be noted, however, that significant advances have been made in emulsion technology so that

Figure 7-2 (C) Comparison prints from four different 35-mm color negatives at various magnifications (1 ×, 4 ×, 8 ×, 16 ×, and 32 ×).

Table 7-1 Comparison of speed and graininess for several panchromatic films intended for pictorial use. (Manufacturers' graininess classifications must be compared with caution since the methods of measurement and specification are not standardized.)

Film Name	ISO (ASA) Speed	Graininess
Plus-X 125	125	Extremely Fine
TRI-X 320 (320TXP)	320	Fine
TRI-X 400 (400TXP)	400	Fine
T-MAX PS3200	3200	Fine
Fuji Neopan1600	1600	Fine

Graininess tends to increase with film speed, but T-Max 100 and 400 speed films are both rated as having extremely fine grain.

the fast films of today are much less grainy than they were some years ago. The measurement and specification of graininess have not been standardized internationally because of this caution needs to be exercised when comparing data from different manufacturers.

Measuring Graininess

It is relatively simple to look at an enlarged print and determine whether or not graininess can be detected. The extent of the graininess, however, is more difficult to assess. It is tempting to make greatly enlarged prints from two negatives and compare them side-by-side for graininess. Although such a method is commonly used in studies of graininess described in photographic magazines and is appropriate for some purposes, it does not actually measure graininess. It is a subjective qualitative method that enables a photographer to say print A looks grainier than print B, but not to indicate the magnitude of the difference. Even when making such simple comparisons it is difficult to make the prints so that there are no other differences to confuse the issue, such as subject, density, contrast, and sharpness.

Various methods have been used in an effort to obtain a reliable and valid measure of graininess. The most widely used method of measuring graininess directly is a procedure called *blending magnification*. Under a set of rigidly specified conditions, a negative that has been uniformly exposed to produce a uniform density is projected onto a screen at increasing levels of magnification, beginning at a level where graininess is not visible. A viewer, seated in a specified position with controlled room-light conditions, is asked to determine when graininess first appears. A numerical value is then obtained by taking the reciprocal of the blending magnification

and multiplying it by 1,000. For example, if the blending magnification is 8, then 1/8 × 1,000 = 125. The number 125 represents the graininess of that negative under the conditions specified, and as the conditions are repeatable, other negatives could be so measured.

A practical alternative to the blending magnification method is to keep the magnification constant but to vary the viewing distance. One can move toward a print until it begins to look grainy. The minimum distance at which graininess is not evident is the *blending distance*, and the number is a measure of graininess. Such blending distance measurements, although practical, are subject to variability.

How a print is going to be viewed must be considered when judging the amount of grain visible. One does not normally view a 16 × 20-inch print at a reading distance of 10 inches, nor an 8 × 10-inch print at a distance of 10 feet. How the final print will be viewed or reproduced is important. Photographs reproduced in newspapers using a 60 lines/inch screen will look grainier than those reproduced in a quality magazine using a 150 lines/inch screen. Motion pictures present an interesting situation, since each frame is in the projector gate for only 1/24 second. When one views a motion picture at a large magnification, as from the front row in a theater, graininess is commonly experienced as a boiling or crawling effect, especially in areas of uniform tone. This is a result of the frame-to-frame change of grain orientation.

It is essential that the density level be specified when making graininess measurements. As shown in Figure 7-3, graininess highly depends upon the density level. With negatives, maximum graininess occurs at a density between 0.3 and 0.6, depending to some extent upon the luminance level

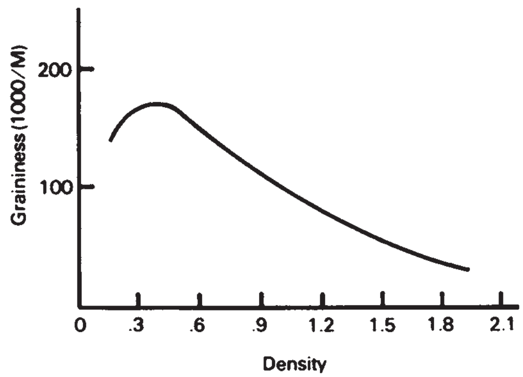


Figure 7-3 Negative graininess is highest at a density of 0.3 to 0.6 and then decreases rapidly as density increases. (The illuminance on the sample is constant.)

of the test field. A density of 0.3 corresponds to a transmittance of one half, which represents equal clear and opaque areas. One would expect little graininess at very low and very high density levels, but for different reasons. At very low densities there is little grain structure. As the density of the negative increases, the amount of light transmitted decreases. The perception of graininess decreases rapidly as the density increases because our ability to see detail and tonal differences decreases at low light levels,.

At a very high density, graininess is not perceptible even though the silver in the negative has a very grainy structure. This can be demonstrated by selecting a negative having a uniform density of about 1.5 and increasing the intensity of the viewing light source 16 times. The appearance of graininess will jump considerably, for in effect the density of 1.5 behaves as though it were a density of only 0.3 with respect to viewing luminance. In fact, if the light level is adjusted so that the transmitted light remains constant regardless of the density level, the result will be the curve shown in Figure 7-4, which indicates that the graininess increases gradually with increasing density.

There is another method of demonstrating that graininess increases

When comparing prints or negatives for graininess, the prints or negatives should match in density, contrast, and sharpness.

Graininess is most easily detected in uniform midtone areas. Condenser enlargers increase graininess.

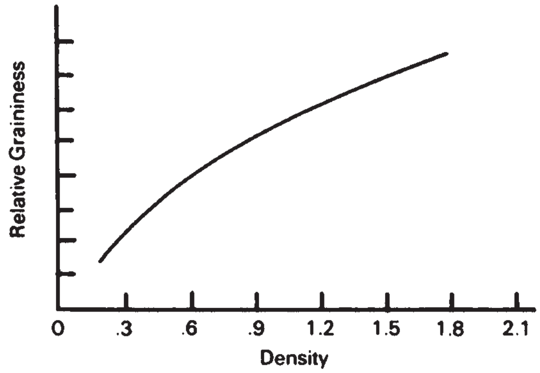


Figure 7-4 Graininess increases as density increases if the light reaching the eye is adjusted so that it is the same regardless of the density of the negative.

with negative density when compensation is made for the lower transmittance that involves making a series of photographs of a gray card with one-stop variations of exposure, from four stops below normal to four stops over. Developing the film normally will produce negatives having nine different density levels ranging from about 0.2 to about 1.5. Each negative is printed at a fixed high magnification with the necessary adjustment in the printing exposure time to produce the same medium gray density on all of the prints. The prints should be viewed side-by-side under uniform illumination and at the same distance to observe differences in graininess.

Considerable variation in the density level at which graininess is most apparent has been found among different types of images such as film negatives, prints, projected black-and-white transparencies, projected color transparencies, black-and-white television, and color television. The density level is higher for color images than for black-and-white, for transparencies as well as television, as shown in Figure 7-5. This is partly due to the scattering of light by silver particles, known as the *Callier effect*. The Callier coefficient, a measure of this effect, is the ratio of the density with specular illumination to the density with diffuse illumination. Since color dyes scatter the light very little, the Callier coefficient is approximately 1.0 with color images. In black-and-white images, the scattering of light and the Callier coefficient increase with density and the size of the silver grains, producing values higher than 1.0.

Recent measurement of graininess for black-and-white and color prints reveals that the black-and-white prints

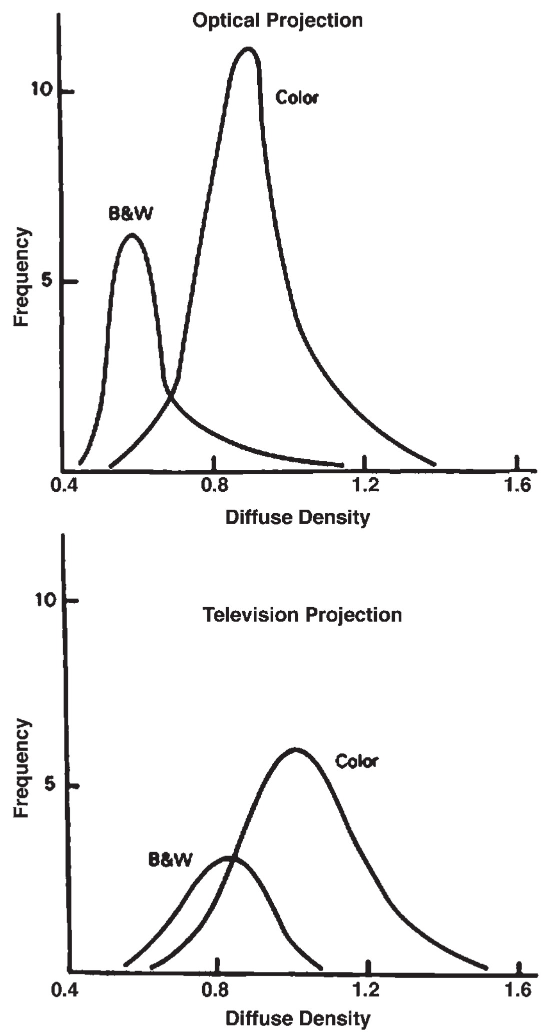


Figure 7-5 The density at which graininess is most objectionable is different for black-and-white and for color films, and for different systems of projection. (The difference between black-and-white and color is due mostly to the Callier Q factor—silver images scatter more light.) (Redrawn from Zwick, D., "Film Graininess and Density: A Critical Relationship," *Photographic Science and Engineering 16:5* (1972), p. 345.)

exhibit peak graininess at a density of about 0.65 and color prints at an average density of about 0.93, with some prints peaking at a low density of 0.80 and others at a high density of 1.05. Further, it was found that varying the level of illumination on prints had little effect on the density at which peak graininess was observed. "An increase in illumination level by a factor of 6.5× increases the critical density by about 0.07. The shift in critical density that would occur between viewing a print in sunlight and with indoor home lighting would be less than 0.2 density."[1] (The illumination level does of course have a pronounced effect on the perceived tone reproduction of a print.)

Grain Size and Image Color

Although we think of the silver image as being black, as the term black-and-white implies, the color can vary considerably between images depending upon the size and structure of the silver particles. Large silver particles absorb light almost uniformly throughout the visible spectrum, producing neutral color images that appear black where the density is high. Smaller silver grains absorb relatively more light in the blue region than in the green and red regions, causing the images to appear more brownish. By making the silver particles sufficiently small, it is possible to obtain a saturated yellow color, as exemplified by the yellow filter layer between the top two emulsion layers in some color films.

When the smallest dimension of small particles approximates the size of the wavelength of light, they scatter light selectively by wavelength, an effect known as *Rayleigh scattering*. Since the scattering varies inversely with wavelength to the fourth power, blue light is scattered most, and the transmitted light appears reddish. Fine-grained negatives that have a brownish color can have different printing characteristics than would be predicted by visual inspection, because of the lower Callier coefficient when printing with a condenser enlarger, and because of the different response of some printing materials to light of different colors—for example, variable-contrast papers.

Granularity

Controlled graininess can be used to create a textured or impressionistic effect. Granularity is the objective measure of density non-uniformity that corresponds to the subjective concept of graininess. Granularity determination begins with density measurements made with a microdensitometer (a densitometer that has a very small aperture) across an area of a negative that has been uniformly exposed and developed. The data are automatically recorded and mathematically transformed into statistical parameters that can be used to describe the fluctuations of density due to the distribution of the silver grains in the negative, and therefore to determine the granularity.

The process can be described graphically as illustrated in Figure 7-6. The fluctuations are greater at a density of 1.0 than they are at a density of 0.3. If all of the many points indicating the variation from an assumed average density are collapsed as shown on the left of the illustrations, a near-normal distribution is generated. Such a curve allows the specification of granularity in statistical terms that may be generalized. For any mean or average density ($\bar{D}$), the variability of density around that mean is specified by the

[1] Zwick, D., "Critical Densities for Graininess of Reflection Prints," *Journal of Applied Photographic Engineering*, 8:2 (1982), p. 73.

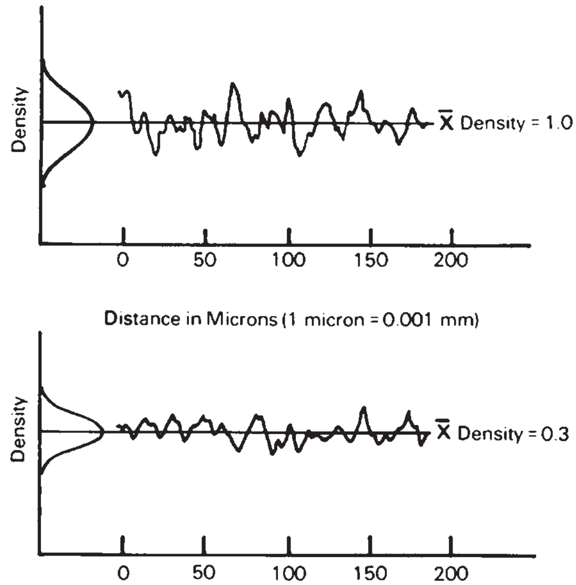


Figure 7-6 Microdensitometer traces of a negative material at a high density and at a low density. The fluctuation of density over micro-areas on the negative describes the granularity of the negative. The higher density of 1.0 has greater fluctuations and therefore higher granularity.

The best way to minimize graininess is to use a fine-grain film.

standard deviation σ (*D*) (read sigma *D*). Because σ (*D*) is the root mean square (rms) of the deviations, such granularity measurements are called rms granularity. (Root mean square is the standard deviation of micro-density variations at a particular average density level.)

Granularity values for Kodak negative films, and reversal and direct duplicating films are made at a density of 1.00. Microdensitometer traces are made with a circular aperture having a diameter of 48 micrometers (0.048 mm).

Since there is a good correlation between granularity measurements and graininess, rms granularity numbers are used to establish the graininess classifications found in some data sheets and data books: *microfine, extremely fine, very fine, fine, medium, moderately coarse, coarse*, and *very coarse grain*. In addition to providing a good objective correlate for graininess, rms granularity is analogous to the way noise is specified in electronic systems. This provides an important linkage for photographic-electronic communication channels and systems. Some typical values of rms granularity for several Kodak films and plates are shown in Table 7-2. They were made with a microdensitometer having a scanning aperture of 48 micrometers, corresponding to a magnification of 12, on a sample having a diffuse density of 1.0.

Kodak has also adopted the KODAK Grain Index. This method replaces the rms granularity value and cannot be compared to rms values. This method is referred to as the Print Grain Index (PGI) and is designed to be more meaningful to a photographer who is accustomed to viewing prints rather than a negative. The PGI utilizes a perceptual scale, equating a two unit change to equal one just noticeable difference (jnd) in graininess. A value of 25 on this scale represents the visual threshold for graininess. A higher value would indicate an increase in the amount of viewable grain. This scale was designed using prints made off a diffusion enlarger and may not be accurate for other printing systems. Other manufactures have developed similar systems.

Table 7-2 **Some Kodak films and their rms granularities. The data represent a very specific set of conditions of testing. Any comparison of rms granularity for other films must be made under the same set of conditions.**

Film Name	Diffuse rms Granularity
Plus-X 125	10
TRI-X 320 (320TXP)	16
TRI-X 400 (400TXP)	17
T-MAX PS3200	18

Minimizing Graininess

Much has been written and claimed about developers for reducing graininess. The same could be said for such claims as was said years ago by Mark Twain when he read his obituary in a newspaper: "Claims are highly exaggerated." Two major problems with claims of reduced graininess are the questionable authenticity of the testing procedures and the failure to completely report difficulties and losses associated with such reduction. Validity of graininess comparison tests requires negatives that have been exposed and developed to produce the same density and contrast, and printed to produce the same tone reproduction. This is a difficult task, and processing the film for the manufacturer's recommended time and temperature seldom produces negatives that meet these requirements. The fact of the matter is that little can be done to improve graininess through development unless one is willing to sacrifice one or more other attributes such as film speed, image sharpness, and tone-reproduction quality. Depending upon the requirements for specific photographic situations, such trade-offs may be warranted, but there is no substitute for beginning with a fine-grained film.

Fine-grain development always results in a loss of film speed. In situations where minimum graininess and maximum film speed are both important, the photographer is presented with a choice of using a high-speed film and a fine-grain developer or a slower film that has finer inherent grain with normal development. The control over graininess by the choice of developer tends to be small compared to the control by the choice of film. Films that are especially designed for microfilming, where high contrast is appropriate and slow speed is tolerable, have a low level of graininess that is truly remarkable. Such films have even been used for pictorial photography by developing them in low-contrast developers in situations where the lack of graininess is a more important consideration than the slow speed.

Graininess of Color Films

Color films exhibit graininess patterns having both similarities and differences, compared with the graininess patterns in black-and-white films. With dye-coupling development, dye is formed in the immediate area where a silver image is being developed so that the dye image closely resembles the grain pattern of the silver image, and the dye pattern remains after the silver image is removed by bleaching. The image structure is more complex with color film due to the three emulsion layers, each containing a different color-dye image. Graininess and granularity are measured and specified in the same manner with color films as with black-and-white. The perception of graininess with color films results from the luminosity (brightness) contribution of the three dye images rather than from the hue and saturation attributes, although the appearance of graininess is not equal for the three colors. The relative contribution of each of the dye layers to granularity is as follows:

Green record	(Magenta dye layer)	60%
Red record	(Cyan dye layer)	30%
Blue record	(Yellow dye layer)	10%

These percentages will vary depending upon the dyes used, but the magenta layer will always be the major contributor to the perception of graininess, mainly because our eyes are most sensitive to green light, which the

magenta dye layer controls. Figure 7-2(B) compares four different 35-mm color-transparency films at various magnifications while Figure 7-2(C) compares prints made from four different 35-mm color negatives at various magnifications (1×, 4×, 8×, 16×, and 32×).

Sharpness/Acutance

Textured paper surfaces obscure graininess.

Sharpness and contrast go hand-in-hand.

Glossy print surfaces enhance contrast and sharpness.

In art, the terms hard-edged and soft-edged are sometimes used to describe the quality of an edge in an image. In photography the term *sharpness* describes the corresponding abruptness of an edge. Sharpness is a subjective concept, and images are often judged to be either sharp or unsharp, but sharpness can be measured. If one photograph is judged to be sharper than another, the sharpness is being measured on a two-point ordinal scale. If a large number of photographs are arranged in order of increasing sharpness, the sharpness is being measured on a continuum on an ordinal scale.

The sharpness of a photographic image in a print is influenced and limited by the sharpness characteristics of various components in the process, including the camera optics, the film, the enlarger optics, and to a lesser extent the printing material. Sharpness and contrast are closely related, so any factor that increases image contrast tends to make the image appear sharper. Similarly, anything that decreases image sharpness, such as imprecise focusing of the enlarger, tends to make the image appear less contrasty.

Although it is not possible to obtain a sharp print from an unsharp negative simply by focusing the image with an enlarger, there are various procedures available for increasing the sharpness of photographic images. Some film developers, for example, produce higher local contrast at the boundaries between areas of different density, which causes the image to appear sharper. The anomaly on the denser side of the boundary is called a *border effect*, the anomaly on the thinner side is called a *fringe effect*, and the two together are referred to as edge effects. There are also electronic and photographic techniques for either making an image edge more abrupt or increasing the local contrast at the edge.

Developing factors that alter edge effects, and therefore image sharpness, include developer strength, developing time, and agitation. Diluting the developer and developing for a longer time with little or no agitation enhances edge contrast and sharpness. Unfortunately, this procedure can also cause uneven development with some film-developer combinations even though it is used routinely with high-contrast photolithographic materials. One developer specifically formulated to enhance image sharpness with normal-contrast films is the Beutler High-Acutance Developer, named after the man who pioneered developers of this type. The formula is:

Sodium sulfite (Na_2SO_3)	5.0 g
Metol	0.5 g
Sodium carbonate (Na_2CO_3)	5.0 g
Water	1 liter

Acutance

Acutance is a physical measurement of the quality of an edge that correlates well with the subjective judgment of sharpness. It is measured in a laboratory by placing an opaque knife edge in contact with the photographic material being tested and exposing the material with a beam of parallel (collimated) light. This produces, after development, a distinct edge between the dense and clear areas, but because of light scatter in the emulsion the

edge has a measurable width. The edge, which is less than 1 mm (1,000 microns) wide, is then traced with a microdensitometer. The result is a change in density with distance. A typical density-distance curve is shown in Figure 7-7. The rate at which density changes as a function of the microdistance of the edge is a graphical description of acutance (sharpness).

The rate of change of density can be expressed in terms of slope or gradient. The average gradient of the curve between two specified points becomes a numerical expression of acutance, as shown in Figure 7-8. Cutoff points A and B establish the part of the curve over which the geometric average gradient will be determined. The gradient $\Delta D/\Delta x$ is found for each of the intervals between A and B. The gradients are then squared, and the squared gradients are added together and divided by the number of intervals to determine the average square gradient. The formula for these calculations is provided in Equation 7-1:

$$\bar{G}^2 = \frac{\Sigma(\Delta D/\Delta x)^2}{n} \qquad \text{(Eq. 7-1)}$$

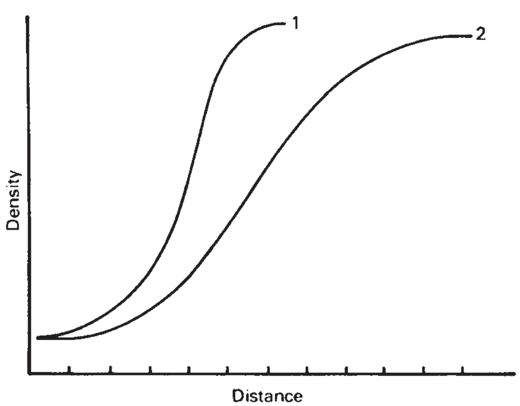


Figure 7-7 The rate at which the density changes across the edge of an image is described by the slope of the curve. The film represented by curve 1 has a higher slope or gradient and therefore has higher acutance and sharpness.

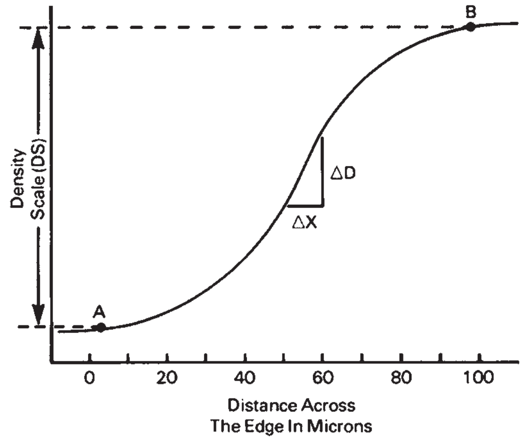


Figure 7-8 To obtain a numerical value for acutance, the average gradient of the curve is calculated and then divided by the density scale (DS).

Acutance is calculated by dividing the average square gradient by the density scale (*DS*) between points A and B on the vertical scale as shown in Equation 7-2:

$$\text{Acutance} = \bar{G}^2 \div DS \qquad \text{(Eq. 7-2)}$$

Resolving Power

Resolving power is the ability of the components of an image-formation process (camera lens, film, projector lens, enlarging lens, printing material, etc.) individually or in combination to reproduce closely spaced lines or other elements as separable. Resolving power is the correlate of the image quality referred to as detail, so that a lens having high resolving power is capable of reproducing fine detail. Targets used to measure resolving power typically have alternating light and dark elements either in the form of parallel bars as in the United States Air Force (USAF) or American National Standards Institute (ANSI) Resolution Targets (see Figure 7-9). Test targets are commonly supplied in high-contrast (black-and-white) and lower-contrast forms because subject contrast influences resolving power.

Alphanumeric resolution targets produce less variability among observers

Resolving power and film speed tend to vary inversely.

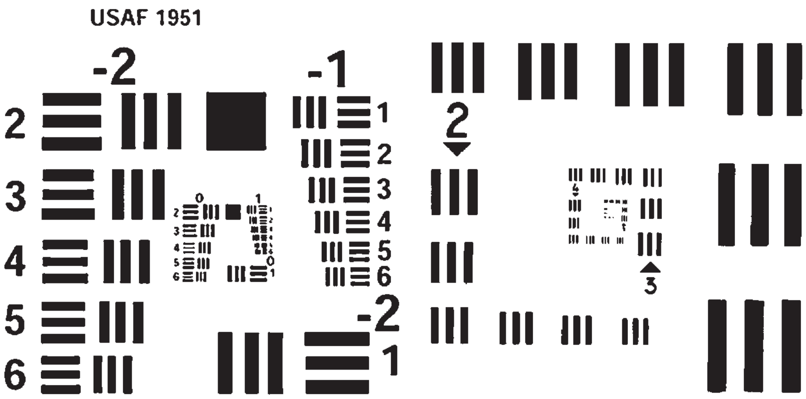


Figure 7-9 Examples of two resolution test targets. Although the USAF and the ANSI targets look different, they are quite similar. Both take the shape of a spiral made up of three black bars that have a square format and decrease in size (increase in line frequency). The USAF target has both vertical and horizontal bars, which allows a check for astigmatism. The ANSI target would have to be rotated 90 degrees and photographed twice to accomplish the same thing.

To test the resolving power of a lens, a target is placed on the lens axis at the specified distance (for example, 21 times the focal length) to produce an image at a specified scale of reproduction (for example, 1/20). The aerial image is examined with a microscope at a power about equal to the expected resolving power, and the finest set of lines or elements that can be seen separately is selected. A conversion table translates this information into lines-per-millimeter resolving power, usually in terms of dark-light pairs of lines. Alternative methods of expressing resolving power are in lines-per-unit-distance in object space rather than in the image, and as angular resolving power.

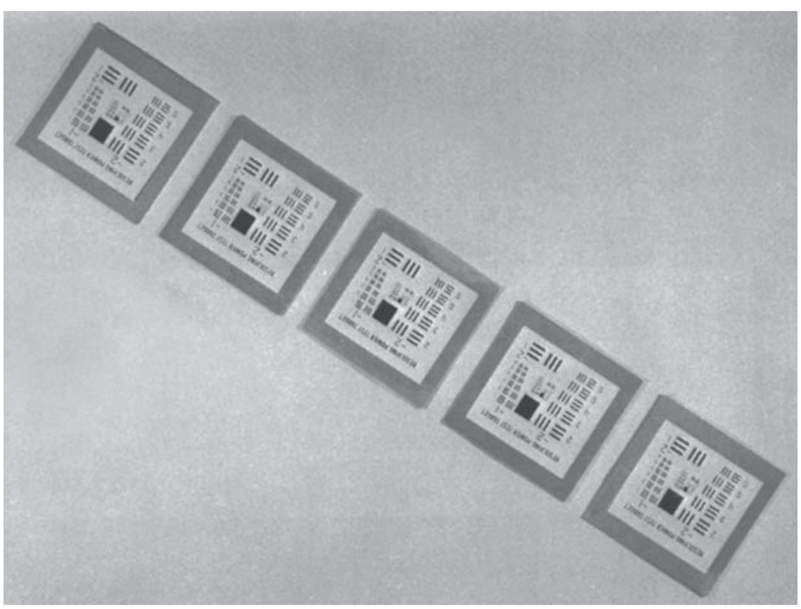


Figure 7-10 Resolution test targets arranged to measure resolving power on and off axis.

Variations can be made in the above procedure to obtain additional information. A row of targets can be used so that the images fall on a diagonal line at the film plane to determine the resolving power for various off-axis angles as well as on-axis (see Figure 7-10). The test can be repeated with the lens set at different *f*-numbers to determine the setting that provides the best compromise between reducing lens aberrations and introducing excessive diffraction. The effect of filters on the optical image can be determined by measuring the resolving power with and without the filter, also with and without compensation for focus shift with the filter.

The relationship between the resolving power of the components of a system and the resolving power of the entire system is commonly expressed with the formula $1/R = 1/r_1 + 1/r_2 + 1/r_3 \ldots$ where R is the resolving power of the system and each r_n is the resolving power of each component in the system. This formula reveals that the resolving power of the system cannot be higher than the lowest resolving power component. In fact, the resolving power of the system is always lower than the lowest component. If, for example, a lens with a resolving power of 200 lines/mm is used with a film having a resolving power of 50 lines/mm, the resolving power of the combination is 40 lines/mm. Thus it would be a mistake to believe that the quality of the camera lens is unimportant for photographs made for reproduction in newspapers and on television, where the maximum resolving power

is relatively low. The only question is whether differences in resolving power of two lenses would produce a noticeable difference in the reproduction.

Since it is not possible to measure the resolving power of photographic film directly, it is common practice to use the film with a high-quality lens of known resolving power, determine the resolving power of the system, and then calculate the film's resolving power. The resolving power of the lens-film combination is referred to as *photographic resolving power* to distinguish it from film resolving power and lens resolving power.

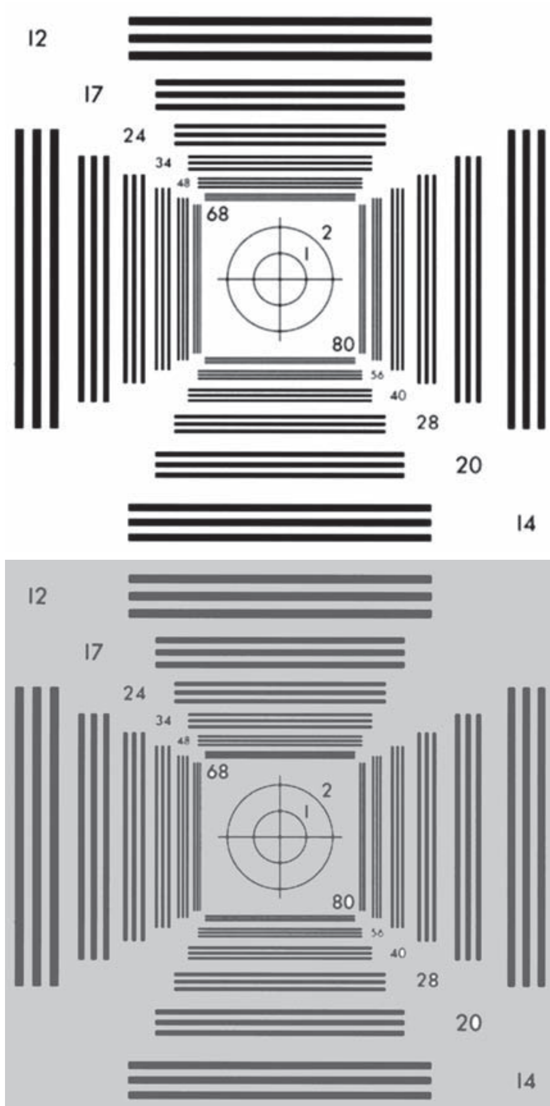


Figure 7-11 High-contrast and low-contrast resolving-power test targets. The target on the top has a contrast ratio of 100:1, while the one on the bottom is 2:1 with the correct exposure.

Resolving-Power Variables

A number of factors can enter into the testing procedure to produce variable resolving-power values, including the following:

Test target contrast. The higher the contrast of the test target, the higher the measured resolving power will be. Black-and-white reflection targets have a luminance ratio contrast of approximately 100:1. The ratio for low-contrast targets may be as low as 2:1 or even less. The transmittance ratio for transparency test targets is generally about 1,000:1. High-contrast and low-contrast test targets are illustrated in Figure 7-11, and comparison data for the two types are presented in Table 7-3.

Focus. Focusing inaccuracies can be caused by human error or mechanical deficiencies. With lenses having residual curvature of field, the position of optimum focus will not be the same for on-axis and off-axis images. Other common problems are a difference between the position of the focusing screen and the position of the film plane, and film buckle. Bracketing the focusing position is sometimes advisable.

Camera movement. Any movement of the camera during exposure will have an adverse effect on resolving power, including the jarring caused by mirror movement in single-lens reflex cameras.

Exposure level. There is an optimum exposure level, with a given film, to obtain maximum resolving power. This level does not necessarily correspond to the published film speed.

The resolving power of a film is higher when measured with a high-contrast test target.

Resolving power changes with exposure, and is highest with the correct exposure.

Table 7-3 Resolution, word, and numerical data for several Kodak films. In general, as the speed of the film increases, resolution decreases. Resolution measured with a high-contrast target is two or more times that measured with a low-contrast target. (Special films such as spectroscopic plates have resolution values up to 2,000 lines/mm but speed values of about 1.0 or less.)

		Resolution in Lines/mm		
Kodak Film	(ASA) Speed	Low Contrast	High Contrast	Resolution Word Category or H.C.
T-MAX 100	100	62	200	Very High
Plus-X	125	50	125	High
T-MAX 400	400	50	125	High

Development. The degree of development affects negative density, contrast, and granularity, all of which can influence resolving power.

Light source. Exposures made with white light and with narrow-wavelength bands of light, ultraviolet radiation, or infrared radiation can produce different resolving-power values for a variety of reasons including chromatic aberration, diffraction, and scattering in the emulsion.

Human judgment. Different viewers may disagree on which is the smallest set of target lines that can be resolved in a given situation. With experience, a person can become quite consistent in making repeated interpretations of the same images. For this reason, resolving power is more useful for comparison tests made by one person than in comparison tests of resolving-power values to published values. Table 7-4 shows the variations in resolving power when six different laboratories tested the same film using high-contrast, medium-contrast, and low-contrast targets. The values represent an average of three tests for each condition. The upper table shows the results before the numbers were rounded off to fit the established ANSI categories. Much of the variation can be attributed to the difficulty viewers have in judging which set of lines is just resolvable.

Table 7-4 Resolution values from six outstanding photographic organizations testing the same film under the same specified conditions. The upper values represent raw data while the lower values are rounded off to fit categories specified by ANSI.

	Testing Laboratory					
Test Target Contrast	A	B	C	D	E	F
High	130	100	140	112	125	126
Medium	105	89	100	100	93	126
Low	53	35	45	36	43	40
High	125	100	125	100	125	125
Medium	100	80	100	100	100	125
Low	50	32	50	40	40	40

"The resolving power of a photographic material is not measurable apart from the other components of the photographic process. What we invariably estimate is the resolution

of a system, including the target, the illumination method, the optical system, the photographic material and its treatment, and the readout method."[2] The same can be said in testing resolution for any system—the resolution of paper copies made on machines such as Xerox, and IBM machines; the resolution of video systems; the resolution of printing plates used in graphic arts printing; the resolution of the human eye; and so on.

Resolving-Power Categories

Since resolving-power numbers mean little to those who are inexperienced in working with them, words are sometimes used to describe resolving-power categories. Eastman Kodak Company has set up the following relationship between words and numbers for films:

Ultra high	630 lines/mm and higher
Extremely high	250, 320, 400, 500 lines/mm
Very high	160, 200 lines/mm
High	100, 125 lines/mm
Medium	63, 80 lines/mm
Low	50 lines/mm and below

Resolving Power And Graininess

The effect of graininess on resolution can be seen in Figure 7-12. The sequence of prints are of a person and a resolution target photographed simultaneously at three increasing distances between subject and camera. All three photographs were made on the same 35-mm film and processed at one time. To obtain the same image size, different amounts of enlargement were required. The first print can be considered normal. Notice that there is detail and texture in the woman's coat and that many of the pine needles are easily distinguishable. Similarly, fine detail is maintained in the resolution target as seen in the small distinguishable lines in the center array. In the second and third prints the fine detail in both pictures has been increasingly obscured by the increase in graininess. The fine detail in the woman's coat, her facial features, the pine needles, and the small bars in the resolution target are no longer distinguishable. The coarser areas of the photograph, however, are still distinguishable as seen by the large array of three-bars and the solid black square in the resolution target, and the vertical black area of the woman's coat. Graininess, which is the major contributor to visual noise in a photographic system, takes over and the signal (information) is diminished or completely lost.

Resolving Power And Acutance

Although image detail and sharpness are commonly perceived as similar, and the corresponding measurements of resolving power and acutance often correlate well, they can vary in opposite directions. That is, one film or lens can have higher resolving power but lower acutance than another film or lens. There was some dissatisfaction with the heavy reliance on resolving power used as a measure of image quality in the past because occasionally a photograph that tested higher in resolving power than another photograph was judged by viewers to be inferior in small image quality. A small loss of fine detail, which corresponds

Resolving power is not a dependable indicator of the appearance of relative sharpness of images.

Land resolution from an orbiting satellite is approximately 20 meters per line pair from a height of about 400 miles.

[2] Todd, H., and Zakia, R. *Photographic Sensitometry*, 2nd ed. Dobbs Ferry, NY: Morgan & Morgan, 1974, p. 273.

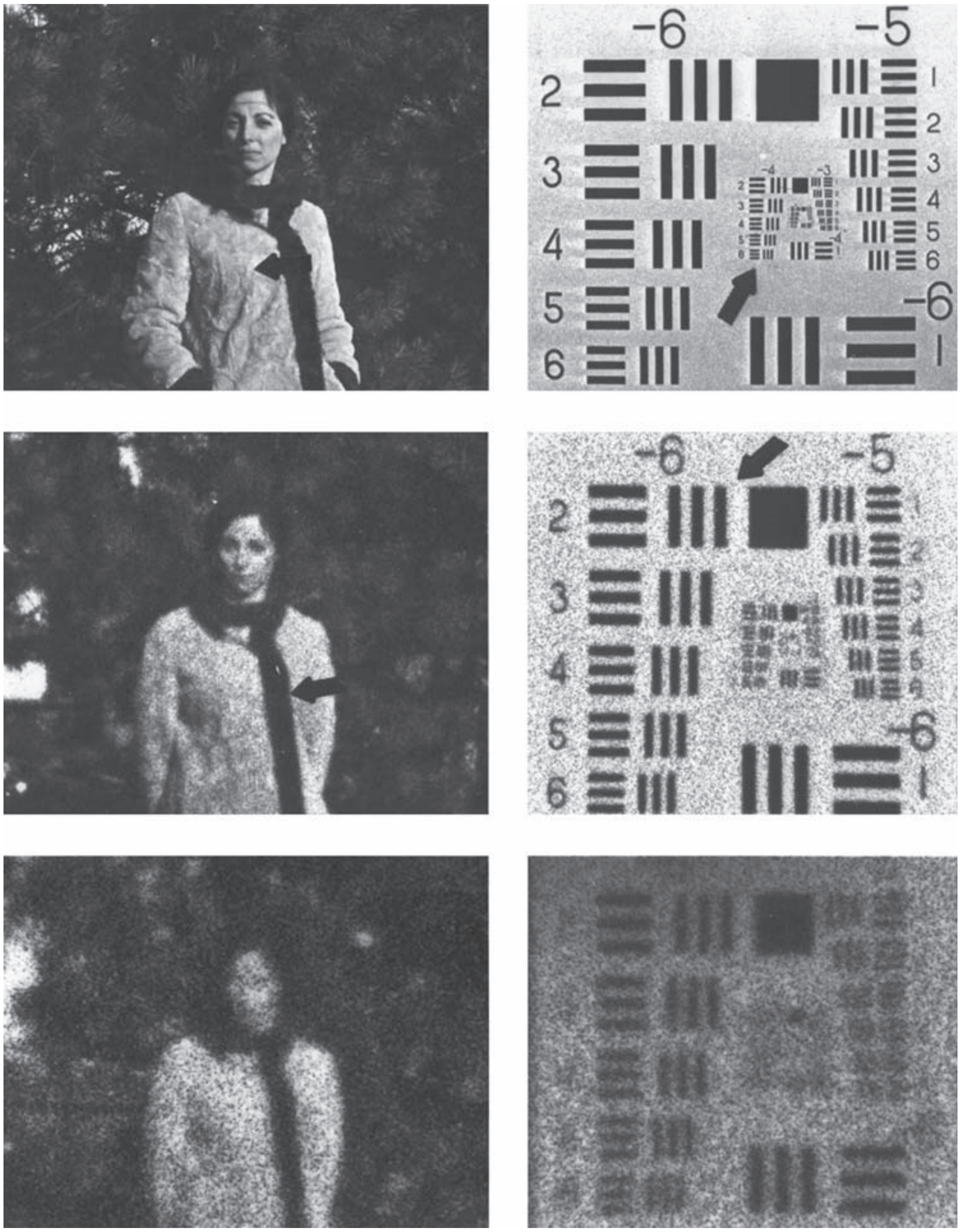


Figure 7-12 The effect of graininess on resolving power. 4 × magnification. 16 × magnification. 32 × magnification. (Photographs by Carl Franz.)

Graininess tends to lower film-resolving power.

to a reduction of resolving power, may be less objectionable esthetically than a loss in sharpness or contrast (see Figure 7-13).

When trying to obtain a reliable and valid measure of image quality, it is tempting to search for a single number that will describe that characteristic. As early as 1958, two research scientists, George C. Higgins and Fred H. Perrin, cautioned: "No single number can be attached to any system to describe completely its capability of reproducing detail clearly."[3]

Modulation Transfer Function (MTF)

The *modulation transfer function* is a graphical representation of image quality

[3] Higgins, George C. and Perrin, Fred H. The Evaluation of Optical Images, *Photographic Science and Engineering*, vol. 2, no. 2, August 1958, pp. 66–76.

that eliminates the need for the observer to make decisions. The MTF system differs from resolving-power measurement in two other important ways. First, the test object generates a sine-wave pattern rather than the square-wave pattern generated by a resolving-power target; second, the percent response at each frequency is obtained. Resolving-power values are threshold values, which give only the maximum number of lines resolved—that is, the highest frequency. Figure 7-14 shows a sine-wave test target, a photographic image of the target, and a microdensitometer trace of the image. Note that the test target increases in frequency from left to right and that the "bars" do not have a hard edge but rather a soft gradient as one would expect from a sine wave.

The modulation transfer function is a graph that represents the image contrast relative to the object contrast on the vertical axis over a range of spatial frequencies on the horizontal axis, where high frequency in the test target corresponds to small detail in an object. If it were possible to produce a facsimile image, the contrast of the image would be the same as the contrast of the test target at all frequencies, and the MTF would be a straight horizontal line at a level of 1.0. In practice, the lines always slope downward to the right, since image contrast decreases as the spatial frequency increases. Eventually the lines reach the baseline, representing zero contrast, when the image-forming system is no longer able to detect the luminance variations in the test target. As with resolving power, an MTF can be determined for each component in an image-forming system or for combinations of components. The MTF for a system can be calculated by multiplying the modulation factors of the components at each spatial frequency.

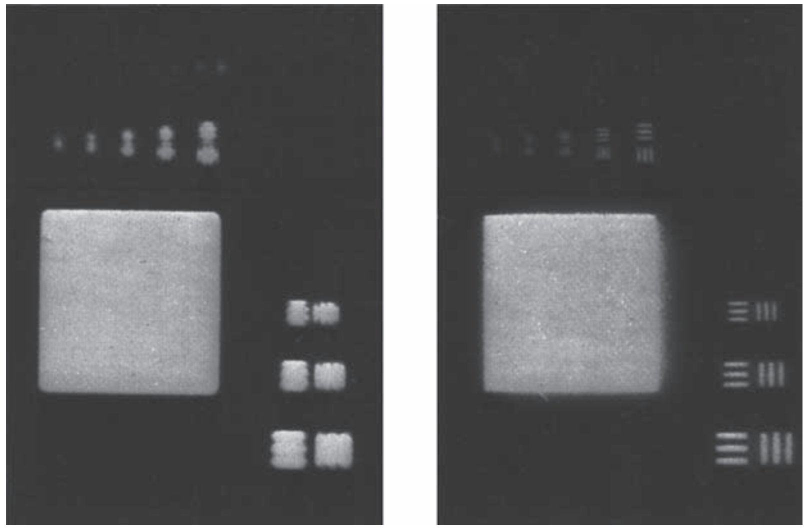


Figure 7-13 Enlargements of small images of a test object made on the same film. The left image was made on the optical axis of the lens where acutance was high but resolving power was low. The right image was made 15° to the right of the optical axis where the acutance was low but resolving power was high.

The advantage of modulation transfer functions is that they provide information about image quality over a range of frequencies rather than just at the limiting frequency as does resolving

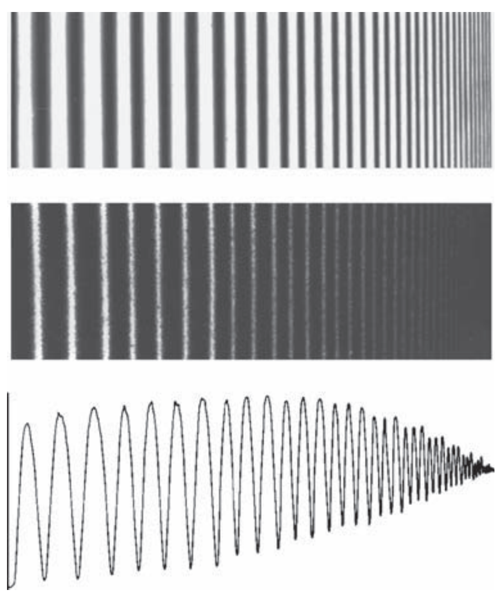


Figure 7-14 To measure modulation transfer functions a sinusoidal test target is photographed and then a microdensitometer trace made of the photographic image. (© Eastman Kodak Company.) (Top) Sine-wave test target. (Middle) Photographic image of test target. (Bottom) Microdensitometer trace of the photographic image of the test target.

power; but there are also limitations and disadvantages. For example, photographers cannot prepare their own modulation transfer functions, and the curves are more difficult to interpret than a single resolving-power number. MTFs are most useful for comparison purposes. Figure 7-15 shows published curves for two pictorial-type films having speeds of 32 and 1250. Although both films have the same response up to about 5 cycles/mm, the response falls off more rapidly for the faster film as the frequency increases, indicating that the slower film will hold fine detail better. It should be noted also that modulation transfer functions for lenses do not provide the desired information about off-axis aberrations such as coma and lateral chromatic aberration. When this information is needed, it is necessary to go through an additional procedure to produce an optical transfer function.

The following is an example of how a system MTF can be determined by multiplying the modulation factors of the components. If the modulation factors at 50 cycles/mm are 0.90 for the camera lens, 0.50 for the film, 0.80 for the enlarger lens, and 0.65 for the printing paper, the product of these numbers, and therefore the modulation factor for the system, is 0.23.

Definition is a broad term that includes sharpness, detail, and graininess.

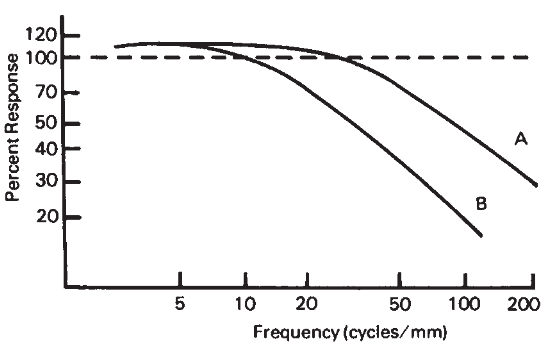


Figure 7-15 MTF curves for two pictorial films with quite different film speeds. Film A is a slow film (ISO 32) and B is a fast film (ISO 1250). One could expect intermediate speeds to fall between A and B. (Output values greater than 100% are the result of adjacency effects in the film.)

Photographic Definition

Photographic scientists and engineers stress the fact that no single number satisfactorily describes the ability of a photographic system to reproduce the small-scale attributes of the subject. The term *definition*, however, is used to describe the composite image quality as determined by the specific characteristics of sharpness, detail, and graininess (or the objective correlates acutance, resolution, and granularity). Definition is applied to optical images, as well as images recorded on photographic materials, although the term optical definition is preferred for the former and photographic definition is preferred for the latter. The modulation transfer function was introduced as a more comprehensive objective measure of image quality since the measured resolving power of a photographic lens, material, or system did not always correlate well with perceived image definition. Because it is difficult to translate modulation transfer function curves into small-scale image quality, photographers have still felt the need for a simple but meaningful measure of definition. One film manufacturer has attempted to satisfy this need by rating its films on the basis of the degree of enlargement allowed, which takes into account the combined characteristics of graininess, sharpness, and detail.

It should be noted that photographic definition is not determined entirely by the quality of the photographic lens and the photographic materials, but also by factors such as focusing accuracy, camera and enlarger steadiness, subject and

image contrast, exposure level, and use of filters. It is not realistic to demand the same level of definition for all types and uses of photographs, including exhibition photographs, motion-picture films, portraits, catalog photographs, and photographs to be reproduced in magazines, newspapers, and on television. Many publications refused to accept black-and-white or color photographs made with small-format cameras long after it had been demonstrated that such cameras were capable of making photographs with better definition than the photomechanical processes were capable of reproducing.

Pixels

In digital photography, a light-sensitive, electrically-charged microchip (either a CCD, CMOS or Foveon X3) serves as the equivalent of film in a camera. Silicon is generally used as a light-sensitive surface and the chip is designed as a rectangular mosaic containing hundreds of thousands of discrete minute areas that act as photoreceptors. Each area is capable of registering picture information and is called a pixel (picture element). (A microchip is also analogous to the retina of the eye, which contains a mosaic of minute light-sensitive receptors called rods and cones, or simply photoreceptors.) Figure 7-16 illustrates a light-sensitive silicon chip. For reproduction purposes only 400 receptors or pixels are shown, whereas in reality they contain as many as half a million pixels within a one-half-inch square area. As light falls on the chip, each pixel generates electrical signals that are proportional to the illuminance. The signals from each pixel are transmitted to a magnetic recording disk. The magnetic image can then be converted to a positive or negative image to be viewed on a monitor or printed on paper to form a "hard copy."

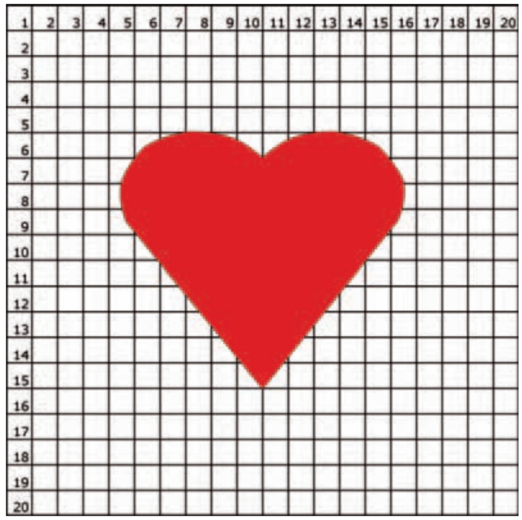


Figure 7-16 A representation of a silicon charge-coupled device (CCD) with 400 squares or pixels. The camera's lens focuses the image of an object or scene on the many light-sensitive discrete surfaces (pixels) of a CCD. The CCD converts the image into an array of electrical charges that are proportional to the intensity of the light falling on each pixel (light-sensitive square).

To specify and compare the image-quality capabilities of a light-sensitive microchip, the term *pixel* is used. The greater the number of separate or discrete pixels possible per unit area of a chip, the higher the potential image quality. Put differently, the smaller the pixels, the more pixels per unit area, and the better the image quality. One way to compare the image-quality potential of a microchip system to a photographic system or other system of picture recording, such as television and graphic arts printing, is in terms of point spread functions, described earlier. The smaller the point spread function of a pixel, the more information that can be packed per unit area.

With this in mind, imagine the 400-pixel chip in Figure 7-16 as having 1,000 pixels within each of the 400 small squares shown.

Pixel means picture element.

Further imagine the overall square being reduced to an area of one-half square inch. This would provide a microchip having 400,000 pixels. Each pixel would be about 0.0008 inch in diameter (about half the diameter of a human hair). In 1983 a one-half-inch-square chip (12.7 × 12.7 mm)—about the size of a fingernail—had a total of about 280,000 pixels. By comparison, Kodacolor film of about the same size used in the 1982 disk camera had a total of about 3 million pixels, each pixel being about 0.0003 inch in diameter. With photographic emulsions, the number of pixels possible per unit area is determined by the granularity and acutance of the emulsion. Current high-end digital camera can have over 21 million pixels present. As a comparison, the human eye contains about 127 million pixels consisting of 120 million rods and 7 million cones all contained in an area about 2 inches square (see Figure 7-17). The cones are much smaller than the rods, the smallest cone receptor being about 0.00008 inch (2 micrometers) in diameter.

Common to all systems of picture recording is the breaking up of a larger continuous optical image into small discrete elements. In photography the discrete picture elements are played back optically, whereas with silicon microchips the information is played back electronically. Since the pixels are discrete photoreceptors, they provide a digital system of recording and playback of pictorial information, as well as text information.

In new micrographic technology, laser beams focused to about one-half micron are used to imprint information on a light-sensitive optical disk as tiny pits or holes. These pixels can be packed closely enough to record the images of 10,000 letter-size documents on a 12-inch-diameter disk.

On a television screen, the individual areas of the phosphors can be thought of as pixels. In the United States, a conventional 525-line television screen consists of 49,152 pixels, 256 in the horizontal direction and 192 vertically (see Figure 7-18). (In Europe a 625-line screen is common. High-resolution screens have about

Figure 7-17 The 120 million rods and 7 million cones in the retina of the human eye can be thought of as a total of 127 million pixels.

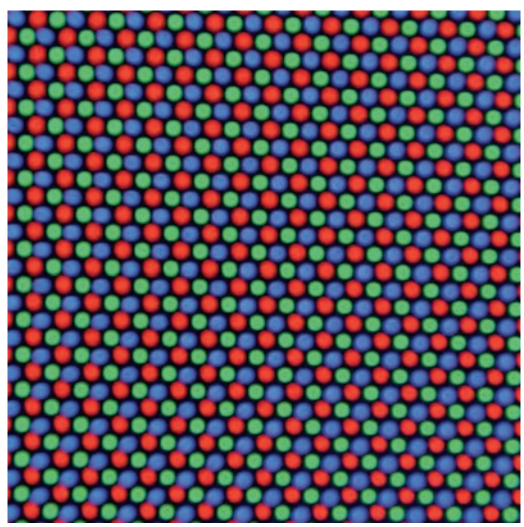


Figure 7-18 Television phosphors as pixels (enlarged view).

1,000 lines.) This provides the level of picture quality seen on broadcast television. A much better picture is available, however, with a TV monitor, which consists of 128,000 pixels (640 × 200), or with higher-resolution monitors such as those with 262,144 pixels (512 × 512). In general, the more pixels per unit area of screen, the better the picture quality (Figure 7-19). There is presently no generally agreed-upon terminology for specifying the resolution of computer-generated images in terms of the number of discrete pixels. However, a qualitative grouping, as shown in Table 7-5, can be helpful. An illustration of the letter A on a low-, medium-, and high-resolution computer slide-generating system is shown in Figure 7-20.

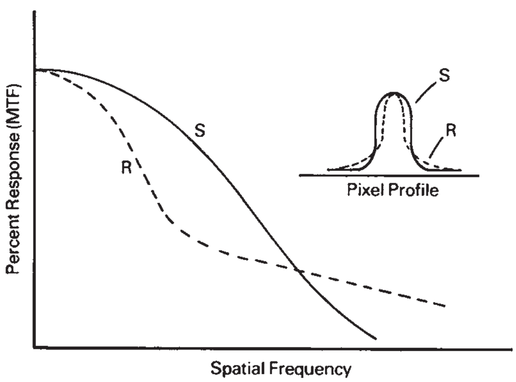


Figure 7-19 Response curves for two hypothetical television tubes. The information displayed by tube S will appear sharper but will have less resolution than that of tube R.

Table 7-5 Arbitrary grouping of pixels in terms of resolution

Computer-Generated Images Resolution		
Pixels	**Total Pixels**	**Resolution Category**
250 × 250[a]	62,500	Low
500 × 500	250,000	Medium
2,000 × 2,000	4,000,000	High
4,000 × 4,000[b]	16,000,000	Very High

[a] On a 19-inch diagonal TV screen, each pixel would have a diameter of about 1/16 inch.

[b] Kodak Ektachrome films can resolve about 3,000 × 4,500 pixels in 35-mm format (1 inch × 11/2 inches) for a total of 13,500,000 pixels. Each pixel would have a diameter of about 0.000.001 (one millionth of an inch).

Digital Resolution

Many of the factors that affect the resolution of a film system also affect the resolution of a digital system. Other additional factors to consider include the number of pixels available and the system electronics that may be altering the digital data by applying image compression or gamma correction. The ISO has established a standard for determining the resolution of a electronic still-picture cameras (ISO 12233). The ISO calls for all resolution measurements to be performed in the digital domain employing digital analysis techniques.

Figure 7-21 illustrates the target that the ISO has specified for use with digital cameras. The target is illuminated at 45° angles from both sides and an exposure made so that the white of the target is near the maximum digital count and there should be no clipping of digital counts in either the white or black areas of the target.

A visual resolution measurement may be made displaying the image on a

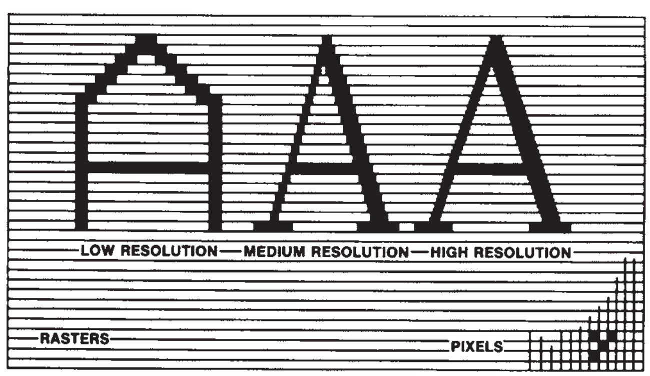


Figure 7-20 This illustration simulates the letter quality obtained by low-, medium-, and high-resolution computer slide-generating systems. (Illustration courtesy of Professor Deane K. Kayton, Audio-Visual Center, Indiana University.)

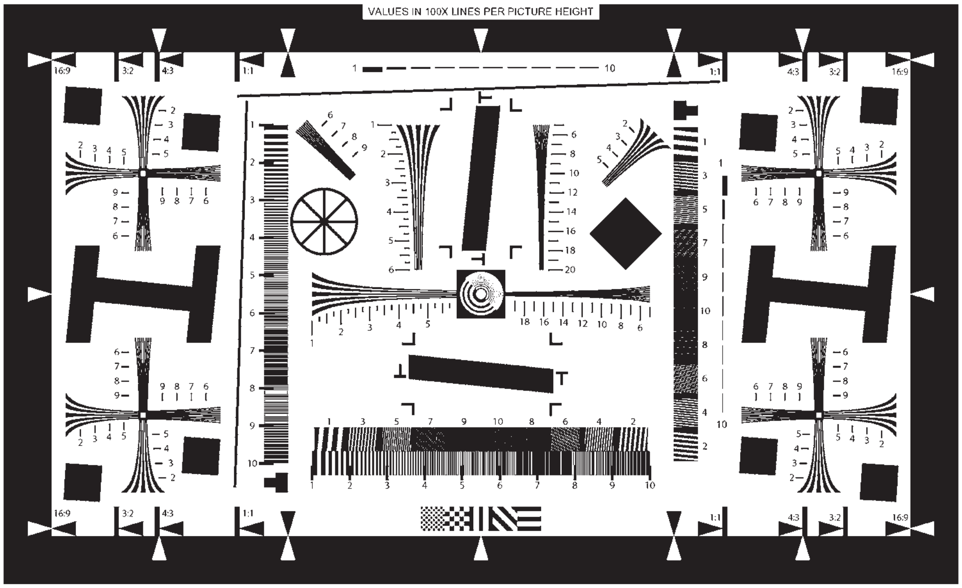


Figure 7-21 Resolution target for electronic still cameras.

monitor or creating a hardcopy image. Care must be taken that the monitor or printer have higher resolution than the camera. Magnification on a monitor is allowed. A spatial frequency response may also be calculated from the target using image processing software.

T-Grain Emulsions

Major advancements in the field of emulsion chemistry have led to films with significantly increased film speed and no loss of sharpness or increase in graininess. In 1982, Eastman Kodak announced a major breakthrough in emulsion technology with their new T-grain emulsion. Figure 7-22 compares a conventional-grain emulsion with the T-grain emulsion at a magnification of 6,000 ×. (An electron microscope was used, as optical microscopes are limited to magnification of about 850 ×.) Notice that the conventional grains are pebble-shaped whereas the T-grains are flat and present a larger surface per unit volume, which maximizes absorption of incoming incident light. The result is a much faster film with about the same amount of silver and no loss in image quality.

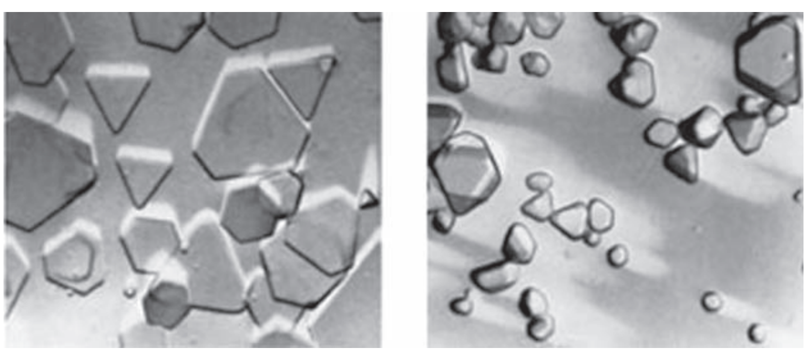


Figure 7-22 Silver halide grains at 6,000 × magnification. The T-grains appear flat and absorb light more efficiently than the conventional pebble-like grains to the right.

REVIEW QUESTIONS

1. The general term that includes sharpness, graininess, and detail is . . .

   A. acutance
   B. tone reproduction
   C. definition
   D. resolution

2. Graininess is most evident in the areas of a print having . . .

   A. a uniform light tone
   B. a uniform medium tone
   C. a uniform dark tone
   D. high-contrast fine detail

3. Some fine-grain silver images appear warm in color because the small particles of silver . . .
   A. transmit red light
   B. oxidize and turn reddish
   C. scatter short wavelength light
4. Granularity is determined by means of calculations based on . . .
   A. blending magnification
   B. blending distance
   C. microdensitometer densities
   D. the number of grains per square millimeter
5. Acutance is an objective term that corresponds to the subjective term . . .
   A. detail
   B. sharpness
   C. graininess
   D. definition
   E. localization
6. Resolving power is an objective term that corresponds to the subjective term . . .
   A. detail
   B. sharpness
   C. definition
   D. recognition
   E. detection
7. If a camera lens has a resolving power of 200 lines/mm and film has a resolving power of 100 lines/mm, the resolving power of the combination is . . .
   A. 50 lines/mm
   B. 67 lines/mm
   C. 100 lines/mm
   D. 200 lines/mm
   E. 300 lines/mm
8. Modulation transfer function graphs represent the relationship between . . .
   A. subject density and image density
   B. image exposure and image density
   C. subject contrast and image contrast
   D. subject resolving power and image resolving power
9. It is estimated that the retina of the human eye contains approximately 127 million pixels (rods and cones). In comparison, television screens in this country contain approximately . . .
   A. 5,000 pixels
   B. 50,000 pixels
   C. 500,000 pixels
   D. 5,000,000 pixels
   E. 50,000,000 pixels

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chapter

8 Filters

Photograph by Professor Glenn C. Miller, Imaging and Photographic Technology, Rochester Institute of Technology.

How Do Filters Work?

When light falls on a surface it can be *reflected, absorbed*, or *transmitted*. A common mnemonic used to remember these is RAT (see Figure 8-1). An object, such as a ball, will reflect the light that strikes it, whereas a stain glass window will do all three, reflect, absorb, and transmit the light that strikes it. The perceived color of any object depends upon the spectral quality of the reflected or transmitted light by that object. When illuminated with white light, an opaque white object will appear white because the surface reflects a high proportion of the incident light at all wavelengths. A black object will appear black because it reflects only a small proportion of the incident light at all wavelengths. In contrast, a red object appears red when illuminated with white light because it selectively absorbs most of the blue and green parts of the white light and reflects most of the red part. Although it will be necessary to consider what happens to the incident light wavelength by wavelength, for now it is sufficient to think in terms of the additive primary colors of light—red, green, and blue—and the additive secondary colors (or the subtractive primary colors)—cyan, magenta, and yellow.

Photographic filters function by removing part of the incident radiation by absorption or reflection, so that the transmitted radiation is of the desired spectral quality. So a green filter will pass green radiation and absorb red and blue radiation (Figure 8-2).

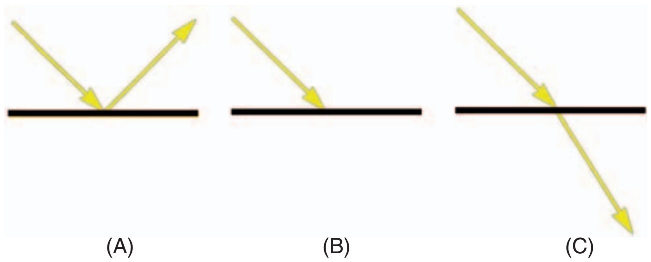


Figure 8-1 Light falling on a surface can be reflected (A), absorbed (B), or transmitted (C).

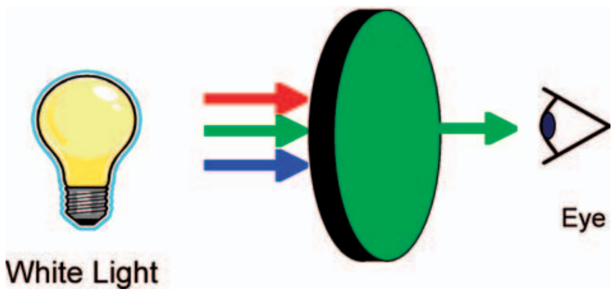


Figure 8-2 A green filter appears green to the eye because the filter absorbs the red and blue components of white light and transmits the green.

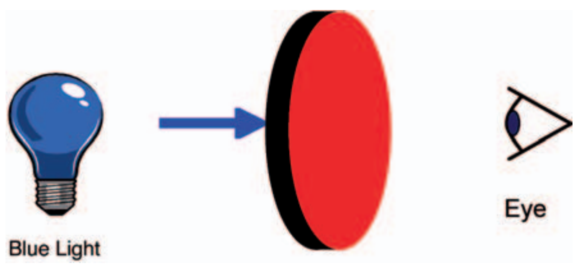


Figure 8-3 The blue light has no red component and therefore will not pass any light to the eye.

Filters work by removing some of the entering light.

Additive primary colors: red, green, and blue

A color filter transmits light of its own color and removes other colors of light.

Filters, of course, cannot add anything to the incident radiation—a red filter cannot transmit red light if there is no red light in the radiation falling on the filter. If a red filter is illuminated with blue radiation, no light will be passed through the filter (Figure 8-3).

Filters can be classified in a variety of ways, but with respect to the effect they have on the incident radiation there are three basic categories. They can be selective by wavelength, thus removing specific wavelengths of radiation, such as with color filters. They can be non-selective by wavelength, such as a neutral density filter that reduces the amount of radiation evenly across all wavelengths. Finally, filters can be selective by angle of polarization, as with a polarizing filter.

Color Filters

Color filters are commonly identified by the perceived color of the transmitted light when illuminated by white incident light (see Figure 8-2). For example, a red filter transmits red light and absorbs green and blue light. Color filters differ with respect to (a) which part of the visible spectrum is transmitted freely (identified by color hue or peak transmittance wavelength); (b) the width of the region transmitted and the sharpness of the cutoff (identified by a general description such as narrow, sharp-cutting bandpass or specific bandpass data); and (c) the degree of absorption of the unwanted colors (identified by general terms such as light yellow and dark yellow, or specific transmittance and density data).

Contrast filters are deep or saturated color filters that almost completely absorb the unwanted colors of light, and are commonly used in black-and-white photography to lighten or darken selected subject colors. Photographers need to be able to predict the effect that such filters will have on subject colors. One method is to look at the subject through the filter and observe which colors are lightened and which are darkened. Accuracy of this process depends upon the film and the eye responding similarly to subject colors. Although panchromatic film and the eye do not respond identically, the responses are sufficiently close to make this a valid procedure.

The *Maxwell triangle* (containing the three additive primary colors—red, green, and blue; and the three additive secondary colors—cyan, magenta, and yellow) can be used to predict the effect of contrast filters on black-and-white photographs without looking through the filters (see Figure 8-4). *The general*

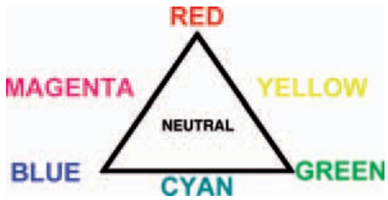


Figure 8-4 The Maxwell triangle can be used to predict the effect of contrast color filters on black-and-white photographs.

A


B


C


Figure 8-5 Image B is a black-and-white version of image A. Image C is taken through a yellow filter. It can be seen that the yellow in the image was lightened as was the red which is adjacent to yellow in the Maxwell triangle.

rule is that a filter will lighten subject colors that are the same color as the filter or are adjacent to that color in the triangle (see Figure 8-5). Thus a red filter will lighten red, magenta, and yellow subject colors in the print, and will darken the opposite color, cyan, and its adjacent colors, blue and green. Note that to lighten yellow and darken red simultaneously, it would be necessary to use a green filter (which is adjacent to yellow but is not adjacent to red in the triangle).

Filter factors are different for daylight and tungsten illumination.

A filter will absorb light making it necessary to adjust the camera exposure to avoid under exposure. The filter factor is a multiplying number that specifies the change in exposure necessary to obtain the same density in a neutral subject area with the filter as without. Table 8-1 provides a list of filter factors and the number of stops they translate to.

A filter factor of 16 corresponds to a 4-stop change in exposure.

The relationship between filter factor and the required number of stops the exposure must be adjusted by is defined by the following relationship, $2^{\text{number of stops}} = \text{filter factor}$. So for example, if the filter being used has a filter factor of 16, the number of stops to increase the exposure by can be found by solving the above equation as follows:

$$2^{\text{number of stops}} = 16$$

Table 8-1 Filter factor and corresponding number of stops necessary to increase exposure

Filter Factor	Number of stops
1	0
1.3	1/3
1.4	1/2
1.5	2/3
2	1
2.5	1 1/3
3	1 2/3
4	2

take the natural log (ln) of each side of the equation

$$\text{number of stops} \times \ln(2) = \ln(16)$$
$$\text{number of stops} = \ln(16)/\ln(2)$$
$$\text{number of stops} = 4$$

A second method, and perhaps easier method, is to divide the logarithm of the filter factor by 0.3. (Recall that 0.3 in neutral density is the equivalent of a one-stop change in exposure). Continuing from the above example with a filter factor of 16

$$\text{number of stops} = \log(\text{filter factor})/0.3$$

$$\text{number of stops} = \log(12)/0.3 = 4$$

If the filter factor adjustment is being applied to the exposure time without a filter, the new exposure time is found by simply multiplying the original exposure by the filter factor. For example, with an initial exposure time of 1/500 second and a filter factor of 16 the new exposure time 1/500 * 16 = 1/30. If the filter factor must be applied to the aperture, it is important to remember that opening the diaphragm by 1 stop doubles the exposure. Continuing with the above example, for a filter factor of 16 the lens would need to be opened up by 4 stops. If the initial *f*-stop was *f*/8, applying the filter factor the new *f*-stop would be *f*/2.

The published filter factor may not always produce the optimum results as factors such as the type of film and development used or the sensitivity of the digital sensor can affect the outcome. This is one reason manufacturers commonly indicate that published filter factors should be modified by the photographer if they do not produce satisfactory results. Two other aspects of the photographic process that must be taken into account in determining

filter factors are the color quality of the illumination and the color sensitivity of the photographic material or digital sensor. Red filters, for example, have larger filter factors with daylight illumination than with tungsten illumination because they absorb a larger proportion of the bluer daylight illumination. Conversely, blue filters have smaller factors with daylight.

An advantage claimed by manufacturers of some cameras having behind-the-lens exposure meters is that the meter automatically compensates for the decrease in the amount of light that reaches the film or sensor when a filter is added. These claims are valid to the extent that the spectral response of the meter corresponds to the spectral sensitivity of the light sensitive material used in the camera. Some difficulty has been experienced in producing meters that have high overall sensitivity as well as the desired spectral response characteristics. A meter with high red sensitivity, for example, will give a false high reading, leading to underexposure when a red filter is used, and a false low reading, leading to overexposure when a blue filter is used.

A simple experiment can be conducted to determine the accuracy of a camera meter with filters. A neutral test card is metered with and without the filters, and the indicated changes in exposure are compared to the published filter factors. Or a gray scale is photographed with and without the filters as the camera meter indicates, and the densities or digital counts of the resulting images are compared.

The objective of the filter factor is to record neutral colors with the same density when the filter is used that they had when it was not used. With this in mind, let's examine why a filter will lighten its own color and those adjacent to it on the Maxwell triangle and darken the others. See Figures 8-4 and 8-6. If the light that is reflected from each object is the total amount of light striking the red filter, assume that it is one unit of light. For a gray object, there are equal amounts of red, green and blue light, however only 1/3 of the total light, the red portion, is passed by the filter. The tone of this object in the final image will not change because the filter factor is applied properly to the exposure. The red object and the two objects whose colors are adjacent to the red object on the Maxwell triangle will be lightened because only a portion of the light is transmitted by the red filter. The remaining cyan, blue and green objects will be darkened because none of the light reflected from them is transmitted by the red filter.

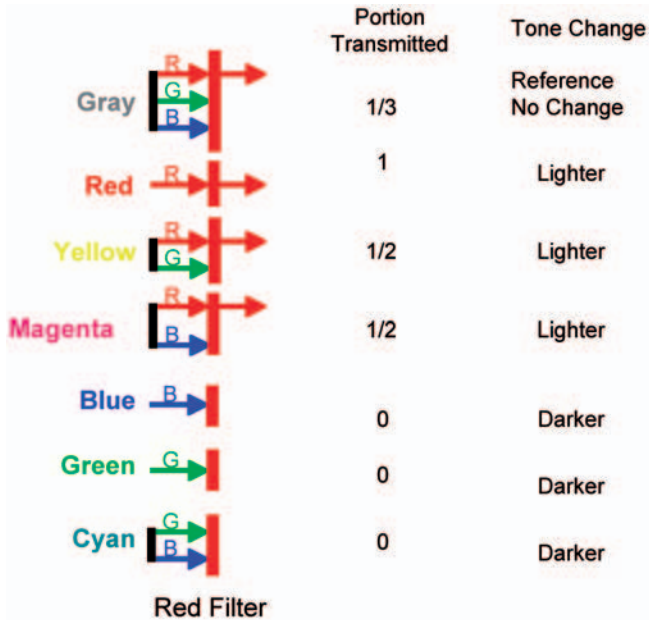


Figure 8-6 A red filter will transmit one-third of white light. The filter will lighten subject colors (in the print) while it transmits more than one-third of the light from the subject and darken subject colors when it transmits less than one-third of the light.

Applying this back to black-and-white photographs created from film the lightening and darkening effects of contrast filters are often not as dramatic as photographers would like. The reason being that subject colors are seldom limited to such a narrow

Aerial haze results mostly from the scattering of light and ultraviolet radiation.

range of wavelengths that the light reflected from the subject is either completely absorbed or completely transmitted by contrast filters as in the example above. Less saturated color filters are produced, however, for situations where more subtle tone changes are desired. For example, a red contrast filter will considerably darken blue sky on a clear day in a black-and-white photograph. A yellow contrast filter will not have as great an effect because the "blue" sky actually contains some green, which is not absorbed by the yellow filter. Subtler darkening can be obtained by switching from a contrast or deep yellow filter to a medium yellow or a light yellow filter.

Panchromatic films used without a filter tend to record blue sky as a little lighter than it appears to the eye due to the ultraviolet radiation in blue skylight, to which films are sensitive, and the slightly high blue sensitivity of panchromatic films with daylight illumination. Panchromatic films, therefore, produce a more realistic reproduction of the lightness of subject colors when used with a light yellow filter than when used without a filter. The recommended yellow filter is classified as a *correction* filter. With tungsten illumination, panchromatic films tend to record reds and blues too light, so a light green filter is used as a correction filter.

Figure 8-7 Both photographs were made on black and white infrared film. The photograph on the right was exposed through a red filter, which transmits red light and infrared radiation but absorbs blue and green light, to which the film is also sensitive. The photograph on the left was made without a filter.

Ultraviolet and Infrared Filters

The silver halides in photographic films are inherently sensitive to ultraviolet radiation and they can be made sensitive to infrared radiation through the use of sensitizing dyes. When the objective is to make a photograph solely with ultraviolet or infrared radiation, a filter is needed that transmits the desired radiation but does not transmit unwanted radiation such as white light. Some UV and IR filters are therefore visually opaque, or nearly so. IR filters are usually used in front of the camera lens so that the film is exposed solely with IR radiation (see Figures 8-7 and 8-8). If the objective is to make surreptitious photographs at night, however, the filter can be used over the flash or other source of infrared radiation so that little or no light is transmitted.

In distant outdoor scenes, ultraviolet radiation often has a deleterious effect on photographs because short-wavelength radiation is scattered much more by the atmosphere than longer-wavelength radiation, creating the appearance of haze, which obscures detail. This *Rayleigh scattering*, as it is called, is inversely proportional to the fourth power of the wavelength of the radiation. To reduce the appearance of haze, a filter should be used that absorbs UV radiation, as well as blue and green light. Thus a red filter effectively reduces the appearance of haze with panchromatic films, and the

effect is even more dramatic when the photograph is made with IR film and IR radiation.

CCD and CMOS sensors in digital camera are sensitive to IR radiation. Many manufactures place an IR cut-off filter internal to the camera to block the cameras sensitivity to this type of radiation. This removes the ability to use a digital camera for IR photography. These filters are not meant to be removed, however a few short minutes on the internet will lead any enterprising photographer to many sites that will provide information as to how to remove these filters. Recently, some digital cameras have come to market that have IR capability such as the IS Pro by Fuji film.

Ultraviolet filters are also often used to block UV radiation in both film and digital photography. Using a UV filter will also darken blue skies and remove some of the effects of aerial haze. Both CMOS and CCD sensors are very sensitive to UV radiation. Manufacturers place filters over the sensor to block most of the UV radiation reaching the sensor; otherwise the exposure and color balance would be affected. Most camera manufacturers do not publish information on the type of internal filtering they employ in their camera designs. This means some testing with and without a UV filter is warranted. Also, many photographers use the UV filter as a protection for the camera lens. It is much more economical to replace a scratched filter than a scratched lens.

Ultraviolet radiation causes certain substances to fluoresce, whereby invisible UV radiation is converted to longer-wavelength visible radiation, revealing useful information about the material (see Figures 8-9 and 8-10). The fluorescent effect may be obscured, however, if the object is also being illuminated

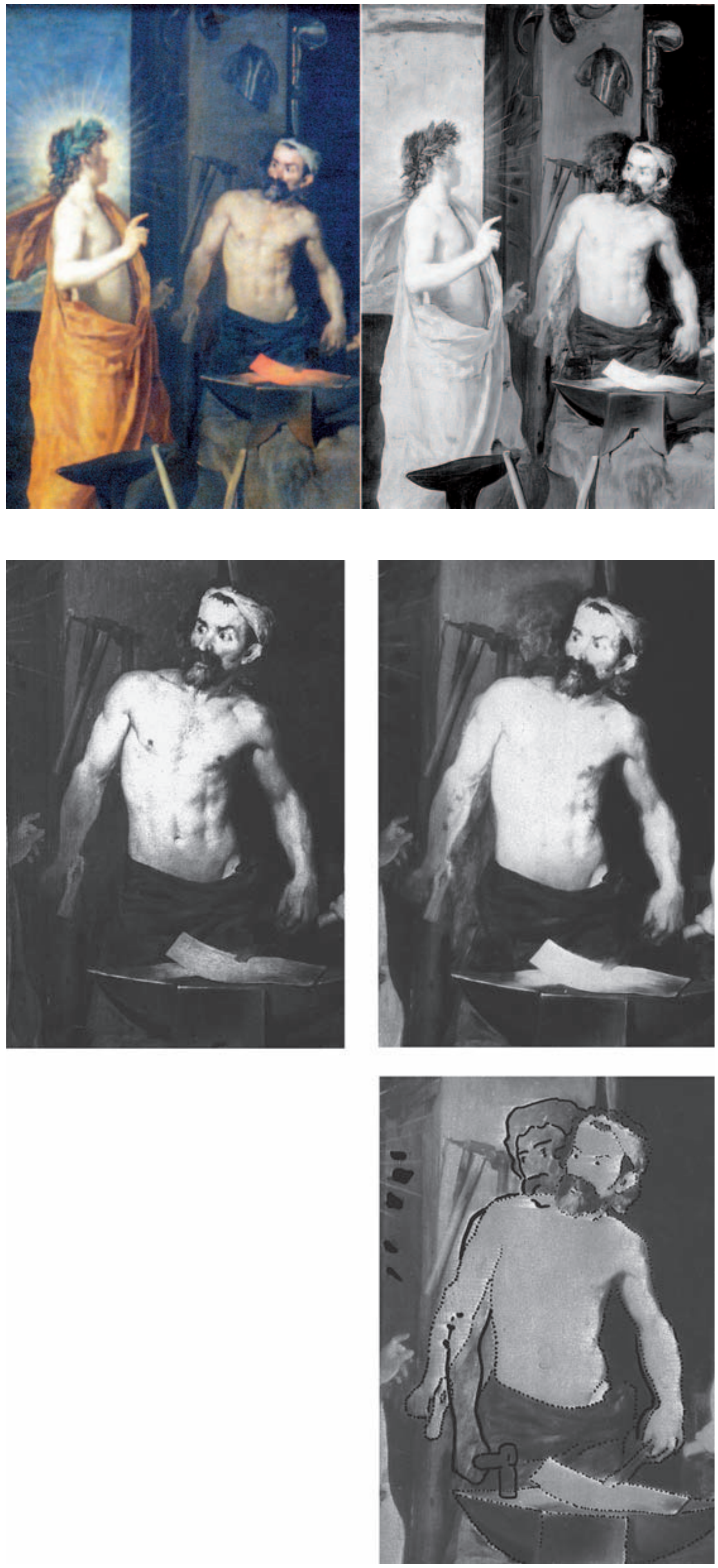


Figure 8-8 (Top left) Photograph of an oil painting. (Top right) Photograph made with black-and-white infrared film and an 87C filter over the camera lens, reveals a somewhat different original painting. The sketch on the right shows the visible image with dotted lines and the differences revealed by the infrared film with solid lines. (Photographs by Andrew Davidhazy.)

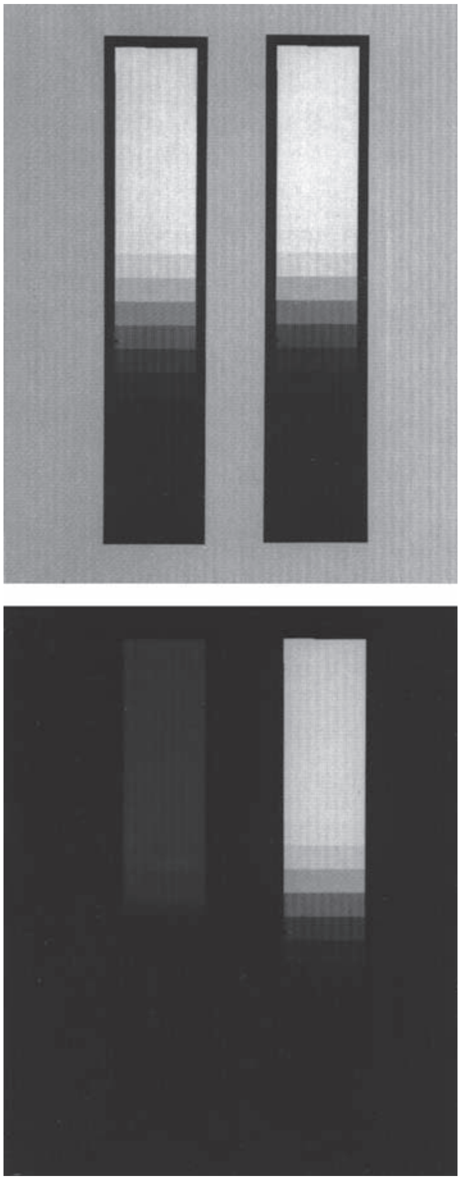


Figure 8-9 A step tablet was printed on a photographic paper containing a fluorescent brightener and on a non-brightener paper. Under tungsten illumination, which contains little ultraviolet radiation, the two prints appear similar (top). With ultraviolet radiation there is a dramatic difference in the appearance of the two.

Fluorescent materials convert invisible UV radiation to longer wavelength light.

with white light from another source. It is common practice, therefore, in fluorescence photography to use two UV filters, one that transmits only UV radiation (known as an *exciter* filter) over the radiation source, and another that transmits light but absorbs UV radiation (known as a *barrier* filter) over the camera lens so that the film records only the visible fluorescence.

Filters for Color Photography

Red, green, and blue contrast filters can be used for color photography as well as for black-and-white photography, for example, to make separation negatives from an original scene with a camera or from a color transparency with an enlarger, and to do tricolor printing with color printing paper. More widely used, however, are less-saturated filters to alter the color temperature of the illumination and to alter the color balance of transparencies and prints. If a photographer wants to use a tungsten-type color film (which is designed to be used with illumination having a color temperature of 3200 K) with daylight illumination having a color temperature of 5500 K, it is necessary to use an orange filter that will lower the color temperature of the light from 5500 K to 3200 K. Conversely, to use a daylight-type color film indoors with studio lights having a color temperature of 3200 K, it is necessary to use a bluish filter that will raise the color temperature of the light from 3200 K to 5500 K. Such filters are identified as conversion or light balancing filters.

The use of color filters for illumination color correction in digital photography presents a unique situation. Digital SLR cameras come with on-board color balancing software. The photographer can choose the preset illuminants such as tungsten or fluorescent and the resulting image should have the correct color balance. Often this can cause a loss in the dynamic range and color fringing in the image as the color corrections are done in software after the image is captured. In many situations

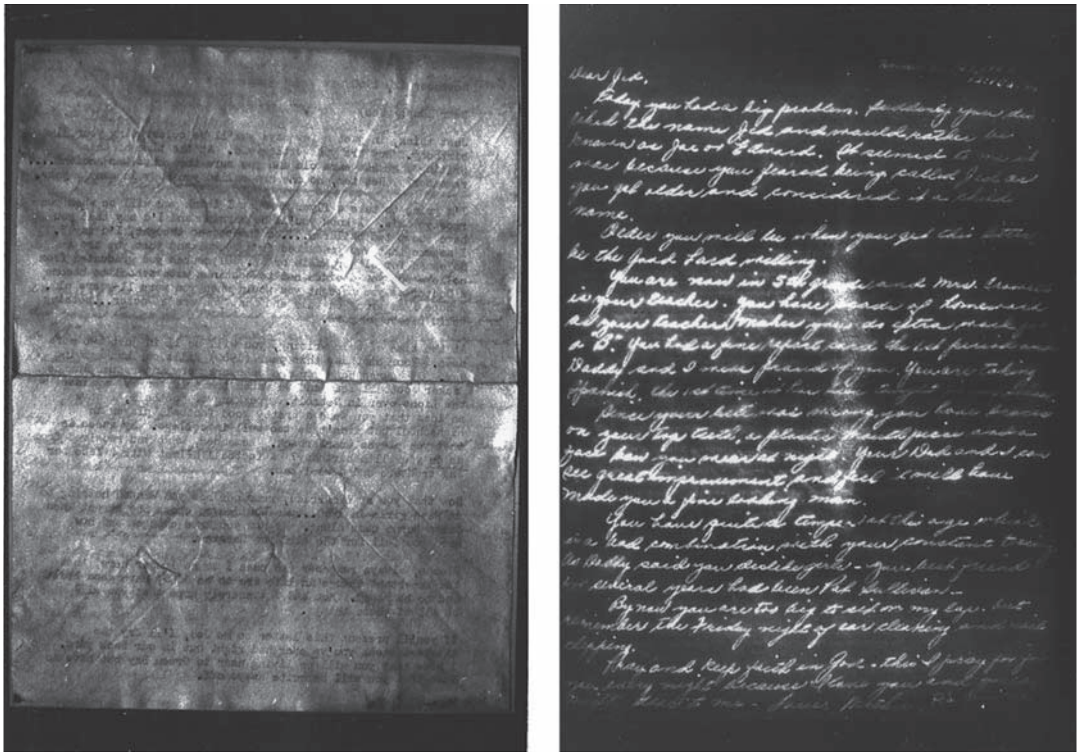


Figure 8-10 Ultraviolet and infrared radiation can sometimes reveal information that cannot be seen or photographed with white light. The water-damaged letter on the left was not legible under normal viewing conditions. The faded lettering, however, fluoresced in the infrared region when illuminated with white light, producing a legible copy when photographed on infrared film with a filter. (Photographs by Andrew Davidhazy.)

the loss in dynamic range may be acceptable and unnoticeable, but not always. To avoid this, the camera can be left in the daylight setting, which is the default for most cameras, and the color temperature of the light source balanced back to daylight using the same methods and filters as with film photography.

Color-compensating (CC) filters are designed to absorb any of the six additive and subtractive primary colors—red, green, blue, cyan, magenta, and yellow. Thus a red CC filter will absorb green and blue light, whereas the complementary color cyan filter will absorb only red light. Color-compensating filters are used on cameras and enlargers to control the color balance of color photographs for the purpose of compensating for variability in any part of the process including the photographic material, the illumination, and the processing—or to create mood or other special effects. CC filters are produced in a range of saturations in each of the six hues, with the saturations calibrated in terms of peak density. Thus a CC30M filter is a magenta color-compensating filter with a density of 0.30 (the decimal is omitted in the designation). Filters are available in densities ranging from 0.025 to .050.

The density of CC filters is based on the maximum absorption, not the proportion, of white light that is absorbed. For this reason, exposure corrections are not derived directly from the density but instead are obtained by trial and error, from the manufacturer's data sheet, or by measuring the transmitted light with a

CC20M + CC20M = CC40M

CC20M + CC20Y = CC20R

Spectrophotometers measure the transmittance of filters wavelength-by-wavelength throughout the spectrum.

meter having appropriate response characteristics. A manufacturer's data sheet for example, suggests a two-thirds stop exposure increase for CC30 filters in all hues except yellow, which is one-third stop.

Even though contrast filters are never sandwiched, because theoretically no light would be transmitted through most combinations, such as red and green, CC filters can be combined to obtain almost unlimited control over the color quality of the image-forming light. When two or more CC filters of the same hue are combined, the densities are additive. The combined density of a CC20M filter and a CC30M filter is the same as the density of one CC50M filter, although it is necessary to increase the exposure by approximately 10% for each additional filter to compensate for light lost caused by surface reflection.

The situation is different when filters of different hues are combined. Sandwiching any two of the three subtractive primary hues—cyan, magenta, and yellow—produces the same effect as a single filter of the resulting additive primary hue and the same density. Thus, CC20M plus CC20Y filters are equivalent to one CC20R filter. Combining equal densities of all three of the subtractive primary hues results in neutral density. Thus, CC20M plus CC20Y plus CC20C is equivalent to a neutral-density filter with a density of 0.20. Combining complementary hues produces the same result; for example, CC20Y plus CC20B is equivalent to a neutral-density filter with a density of 0.20. When three or more CC filters are combined, as in color printing, it is usually better to eliminate any neutral-density combinations unless the resulting shorter exposure time would be inconveniently short.

Note that combining two of the additive primary hues is not exactly equivalent to using one filter of the corresponding subtractive primary hue. For example, combining equal densities of red and green results in a greater absorption of blue, as with a single yellow filter, but there is also a neutral-density effect because the red filter absorbs blue and green, and the green filter absorbs blue and red.

Spectrophotometric Absorption Curves

The general type of filter data discussed above is usually sufficient to meet the needs of most photographers. However, when more specific information is required for technical and scientific applications, *spectrophotometric* curves that show the absorption characteristics of filters throughout the spectrum are useful. In the spectrophotometer, white light is dispersed to form a spectrum. A narrow slit permits the measurement of the *transmittance* of a filter to a narrow band of wavelengths as the spectrum is scanned from the short-wavelength ultraviolet radiation through the visible region to the long-wavelength infrared radiation. Since the transmittance is based on a comparison of the transmitted beam to the unfiltered reference beam, the specific response characteristics of the sensor are unimportant as long as it responds to the full range of wavelengths of interest.

Spectrophotometric curves typically represent wavelengths on the horizontal axis and transmittance and density values on the vertical axis, with the baseline representing 100% transmittance, or a density of 0. As illustrated in Figure 8-11, the transmittance scale on the vertical axis is a *ratio* scale, which provides uniform values for the smaller divisions.

Curves for red, green, and blue tricolor contrast filters are shown in

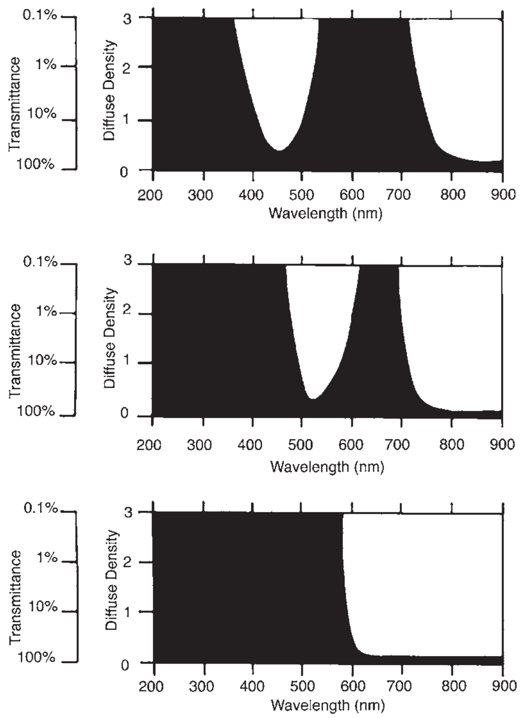


Figure 8-11 Spectrophotometric curves for blue, green, and red tricolor contrast filters.

Figure 8-11. The maximum transmittance (minimum density) is in the wavelength region that identifies the hue of the filter. It can also be seen that the curves do not neatly divide the visible spectrum into thirds (it is impossible to obtain colorants that have perfectly sharp-cutting characteristics at the desired wavelengths), and that all of the filters transmit infrared radiation freely. Infrared radiation transmittance is of little consequence with respect to tone reproduction if the photographic material or digital sensor is not sensitive to infrared radiation.

Furthermore, the curves reveal that some filters do not transmit their own colors freely. The red filter comes the closest to the ideal with a maximum transmittance of more than 90% in the red region beyond 630 nm. The blue filter has a maximum transmittance of approximately 50% to blue light, and the green filter has a maximum transmittance of only 40% to green light. It is difficult to obtain colorants with all of the desired characteristics for use in filters and in color films. Color *masking*, which is used in negative color films and in some color-printing processes, is necessitated by the unwanted absorption of certain colors of light by the cyan and magenta image-forming dyes.

Neutral-Density Filters

0.30 neutral density = 1 stop
0.15 neutral density = 1/2 stop
0.10 neutral density = 1/3 stop

Density = log(Opacity)
Transmittance = Transmitted Light/ Incident Light
Opacity = 1/Transmittance

Neutral-density (ND) filters are used to reduce the illuminance by a known factor in cameras and other optical systems. The intent is to have the same transmittance for all wavelengths of radiation within specified limits. ND filters are usually calibrated in terms of white-light density. A filter with a neutral density of 0.3 has an opacity and filter factor of 2 (the antilog of 0.3) and a transmittance of 1/2 (the reciprocal of the opacity). Some ND filters have been calibrated in terms of stops, where each 0.3 in density corresponds to one stop. ND filters offer an alternative method of controlling exposure when the conventional aperture and shutter controls are inadequate. With highly sensitive photographic materials, a combination of the smallest diaphragm opening and the highest shutter speed may result in overexposure at high illumination levels. There are also situations in which the diaphragm opening is selected to produce a certain depth of field and the shutter speed is selected for a certain action stopping capability rather than for exposure considerations. With some motion-picture cameras, the shutter setting is not a useful exposure control.

ND filters provide a convenient method of obtaining accurate small decreases in exposure. A 0.1 ND filter

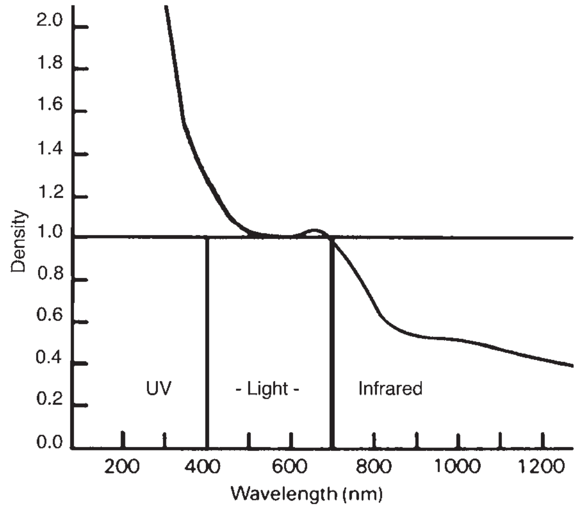


Figure 8-12 Gelatin neutral density filters containing dyes and finely divided carbon absorb too much blue light and ultraviolet radiation and too little infrared radiation.

reduces the illuminance by the equivalent of one-third stop, 0.15 corresponds to one-half stop, and 0.2 corresponds to two-thirds stop.

In black-and-white photography, a ND filter need not be entirely neutral with respect to the absorption of the different colors over the visible part of the spectrum. The relatively low-priced gelatin ND filters, which use carbon and dyes as light-absorbing materials, absorb somewhat more in the blue region (see Figure 8-12).

The gelatin in gelatin filters absorbs UV radiation but transmits light and infrared radiation freely.

A more dramatic deviation from neutrality is noted in the ultraviolet region below 400 nm, where the density increases, and in the infrared region above 700 nm, where the density decreases. Clear gelatin and glass absorb considerable ultraviolet radiation. Thus, the gelatin in the ND filter and in the photographic emulsion if using film, and the glass lens in the camera or enlarger, absorb some (but not all) UV radiation. When photographs are to be made entirely with UV radiation, special precautions must be taken to minimize this absorption in the optical system, such as by substituting a quartz lens and avoiding use of gelatin and glass filters.

Pinhole cameras have no lenses and can be used to record ultraviolet radiation.

Most gelatin neutral-density filters absorb a little blue light and therefore appear slightly yellowish.

On the other hand, when UV radiation interferes with obtaining the desired effect, as in color printing, a special filter may be required to completely absorb the unwanted UV radiation. The excess IR radiation transmitted through ND filters will have no effect on light-sensitive materials that are not sensitive to these wavelengths, but it can introduce exposure errors if the exposure is based on meter readings made with a meter that is sensitive to IR radiation.

Some of the absorbing materials other than dyes that are used in ND filters include carbon, finely divided particles of photographic silver, and thin layers of metallic alloys deposited on a transparent base by evaporation in a vacuum. Colloidal carbon used in gelatin ND filters is somewhat yellowish, requiring the addition of dyes to reduce the deviation from neutrality. Larger carbon particles are more nearly neutral, but they scatter the light more, so these filters are not suitable for use in imaging systems.

The color of finely divided particles of silver depends upon their size. Most black-and-white negatives appear quite neutral in color, but negatives made on fine-grained film developed in a fine-grain developer appear somewhat warmer in color. Even smaller particles of colloidal silver function as an efficient yellow filter in the *Carey-Lea* filter layer, used in color films to prevent blue light from reaching the green-blue and red-blue sensitive layers.

Graduated Neutral Density Filters

The graduated neutral density filter is a filter that is used mostly in outdoor

photography when the dynamic range between the sky and the earth is greater than the dynamic range of the digital sensor or film. The filter is clear on the bottom half and has neutral density across the top half. They are straight across the middle where the transition from no neutral density to neutral density takes place. This allows the photographer to capture detail in both the sky and the ground with one exposure. See Figure 8-13.

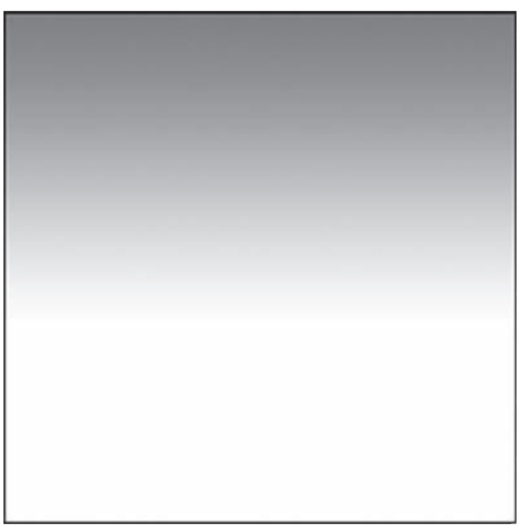


Figure 8-13 Example of a graduated ND filter.

Interference Filters

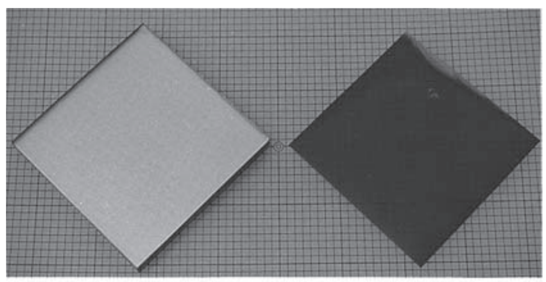
Traditionally, photographic filters have consisted of colorants that absorb the unwanted part of the incident radiation and transmit the desired part, suspended in transparent materials. Interference filters typically consist of thin layers of metallic alloys separated by thin layers of transparent dielectric materials. In these layers the refractive indexes and thicknesses are controlled so that constructive and destructive interference separates the wanted and unwanted components of the incident radiation by means of reflection and transmission (see Figure 8-14).

Interference filters reflect, rather than absorb, unwanted light.

Polarizing Filters

Reflections viewed at an angle of 35° to nonmetallic surfaces can be eliminated with a polarizing filter.

A ray of ordinary light can be visualized as consisting of waves that undulate in all directions perpendicular to the line of travel. Under certain conditions the light can become plane polarized so that there is only one set of waves, and the undulation is restricted to a single plane—like that produced in a rope when one end is snapped up and down. Polarization occurs, for example, when light is reflected as glare at an appropriate angle from most nonmetallic surfaces. The angle at which the polarization is at a maximum varies somewhat with the reflecting material. For precision work, this angle—called the *Brewster angle* or the *polarizing angle*—can be determined from Brewster's law, which states that the tangent of the angle equals the index of refraction of the reflecting



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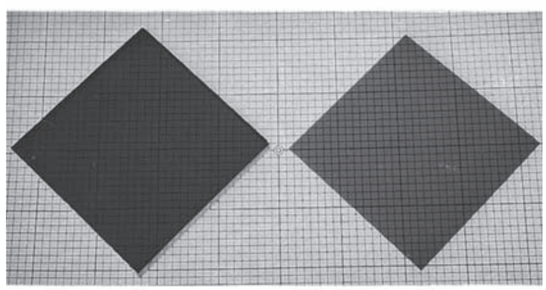

B

Figure 8-14 A dichroic filter (left) and a gelatin filter (right) were placed on a translucent grid on an illuminator. With the room lights on and the illuminator off, the dichroic filter looks like an opaque mirror (top left). With the room lights off and the illuminator on, the transparency of both filters is evident (bottom).

material. For example, if the glass in a window has an index of refraction of 1.5, the tangent of the polarizing angle equals 1.5, and the angle equals the inverse tangent of 1.5 or 56°.

In optics, angles of incidence and reflection are measured to the normal, a line perpendicular to the surface. When eliminating reflections in practical picture-making situations, it may be more convenient to measure the angle of reflection to the surface, which in this example would be 90° − 55° = 35° (see Figure 8-15). Because the polarizing angle does not vary greatly with the different reflecting materials ordinarily encountered, and the polarizing effect decreases gradually with deviations from the polarizing angle, an angle of 35° to the surface is commonly used.

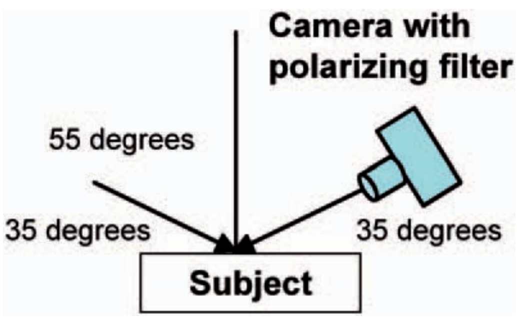

Figure 8-15 Orientation of camera and illumination.

An artificial method of polarizing light is to pass ordinary light through a polarizing filter, which contains very small crystals all oriented in the same direction. The crystals transmit light waves oriented in the same direction and absorb light waves oriented at right angles—thus the transmitted light is plane polarized. Placing a polarizing filter in front of the eye or camera lens and rotating it to the proper position will absorb the polarized light of glare reflections from nonmetallic surfaces at an angle of approximately 35° to the surface. Therefore, the detail that had been obscured by the reflection can be seen and photographed (see Figure 8-16).

Figure 8-15 illustrates the proper camera and subject orientation to use when dealing with reflective surfaces. The orientation changes if the goal is to darken the sun (see Figure 8-17). To achieve this, point an index finger toward the sun and extend the thumb out to ninety degrees. The camera should point in the direction of the thumb to achieve the darkest sky possible.

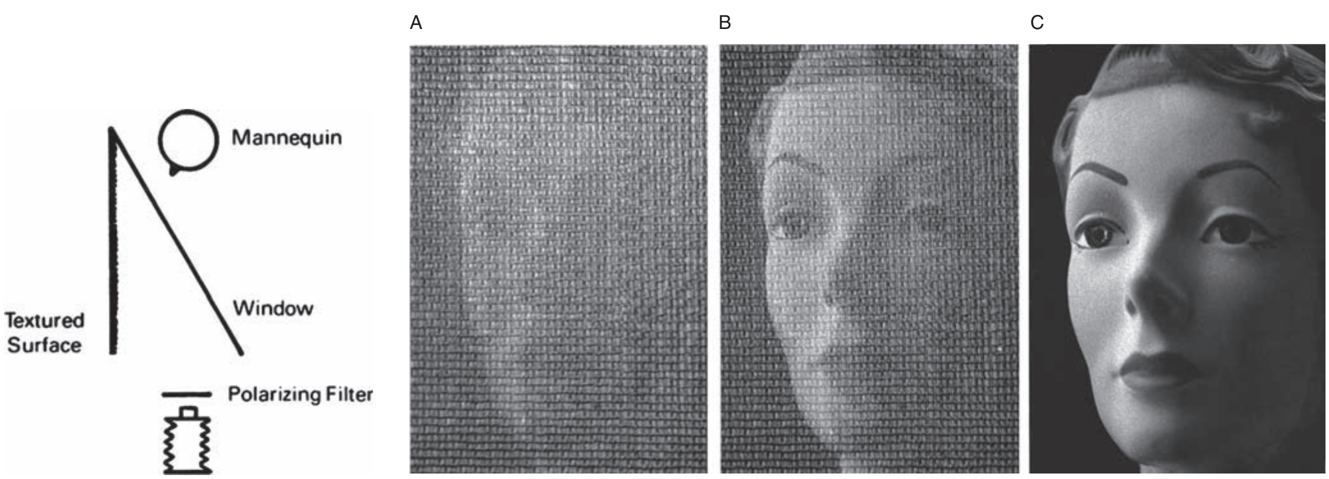

Figure 8-16 A reflection of a textured surface on a window obscures the object behind the window (A). Rotating a polarizing filter in front of the camera lens provides control over the reflection, which is reduced in photograph B and almost entirely eliminated in photograph C.

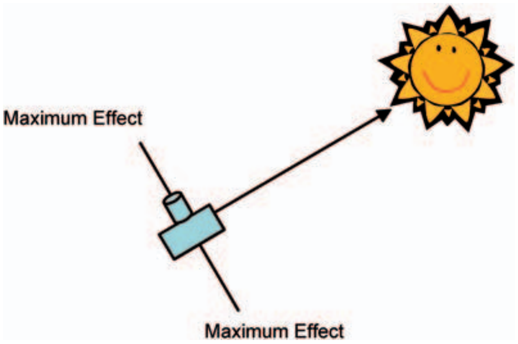

Figure 8-17 Camera and sun orientation for darkening the sky.

The two types of polarizing filters are linear and circular. Most SLR cameras and all digital SLR camera that have through-the-lens metering will require the use of a circular polarizer. These cameras use a beam splitter to achieve the metering and require a circular polarizer to function properly. A polarizing filter will reduce the reflection from glass and non-metallic reflective surfaces, darken blue sky, and increase contrast and color saturation.

Under controlled lighting conditions in-doors, glare reflections can be removed from both metallic and non-metallic surfaces with the camera at any angle to the surface provided the subject is illuminated with polarized light (by placing a polarizing filter in front of the light source) in addition to using a polarizing filter on the camera (see Figure 8-18). With polarizing filters over the light sources, surface glare reflections consist entirely of polarized light and thus can be removed with the camera filter; the polarized light that penetrates the surface, however, becomes depolarized and thus can be used to record the detail under the reflections. Polarized light is commonly used in copying textured surfaces, such as oil paintings. The filter on the camera must be rotated at a right angle to the direction of rotation of the filters in front of the light sources.

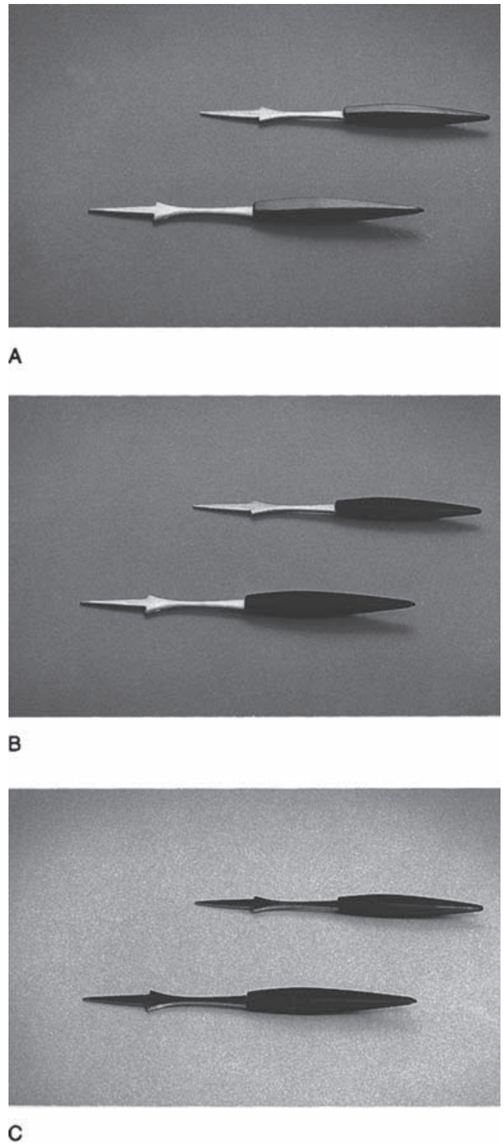

Figure 8-18 A single polarizing filter on the camera lens can eliminate the reflections on the black plastic parts of these objects because the camera angle to the reflecting surfaces is approximately 35°, but the filter has no effect on the reflections on the metal parts (B). When a polarizing screen is placed in front of the light source producing the reflections so that the reflection on the metal consists of polarized light, the filter on the lens can remove the reflections (C).

Crossed polarizing filters can be used to reveal stress patterns in transparent plastic items by placing the objects between the two filters, using *transillumination*. The stress patterns are revealed as areas of varying colors

Figure 8-19 A plastic compact flash card was placed on a large polarizing filter on an illuminator. A second polarizing filter was rotated 90 degrees and placed on, leaving the right end uncovered. Stress patterns in the plastic are revealed as areas of varying colors. (Photography by Jessica Peterson, Biomedical Photographic Communications student, Rochester Institute of Technology.)

and densities (see Figure 8-19). A similar technique is used in photomicroscopy to reveal the structures of crystalline materials.

REVIEW QUESTIONS

1. A yellow object appears yellow when viewed with white light because the object . . .

   A. reflects 580 nanometer wavelength radiation
   B. absorbs light nonselectively
   C. reflects blue light
   D. absorbs blue light
   E. absorbs yellow light

2. A practical use for the Maxwell triangle is to . . .

   A. determine how many different hues there are in white light
   B. determine how many primary colors there are in white light
   C. predict the effect filters will have on photographic exposure
   D. predict the effect filters will have on contrast index
   E. predict the effect filters will have on color reproduction

3. In terms of the final black-and-white photographic print, a red filter used on the camera should darken . . .

   A. cyan, magenta, and yellow objects
   B. red, yellow, and magenta objects
   C. white, gray, and black objects
   D. cyan, blue, and green objects
   E. red, green, and blue objects

4. A filter factor of 8 corresponds to a change in exposure of . . .

   A. one stop
   B. two stops
   C. three stops
   D. four stops
   E. five stops

5. The maximum reduction in the appearance of haze occurs when the image is recorded entirely with . . .

   A. ultraviolet radiation
   B. blue light
   C. green light
   D. red light
   E. infrared radiation

6. The color of the recommended filter for use with tungsten-type color film and daylight illumination is . . .

   A. orange
   B. blue
   C. green
   D. cyan

7. Superimposing a CC05R filter and a CC30R filter is equivalent to a single . . .

   A. CC15R filter
   B. CC25R filter
   C. CC35R filter
   D. CC150R filter
   E. None of the above

8. Superimposing a CC20Y filter and a CC20M filter is equivalent to a single . . .

   A. CC10R filter
   B. CC20R filter
   C. CC40R filter
   D. ND 0.20 filter
   E. ND 0.40 filter

9. To eliminate reflections when copying an oil painting, with the camera axis perpendicular to the surface of the painting, it is necessary to use . . .

   A. two polarizing filters in front of the camera lens
   B. a polarizing filter in front of each light source
   C. a polarizing filter in front of each light source and a polarizing filter in front of the camera lens

10. A neutral density filter used with color film could cause a shift in the . . .

    A. red direction
    B. green direction
    C. blue direction
    D. yellow direction

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chapter

9

Color

Photograph by Derrick Clark, www.derrickrayclark.com

Introduction

The visual experience of perceiving color does not depend upon language or numbers, but the communication of information about the experience does. It is important that we use an agreed-upon and established vocabulary to talk about color. In the past, various disciplines including photography, art, and graphic arts have had difficulty communicating with each other due to the absence of an agreed-upon common color language. The Munsell Color System and the Standard CIE System

A red object illuminated with blue light appears black.

of Color Specification have emerged as two of the more successful attempts to organize the variables of color into a universally accepted system. In addition, the Inter-Society Color Council has brought together representatives of the various disciplines in an effort to lower the barriers to communication. The stated aims and purpose of the organization are "to stimulate and coordinate the work being done by various societies and associations leading to the standardization, description and specification of color and to promote the practical application of these results to the color problems arising in science, art and industry."

Before examining color systems, however, it is necessary to establish a definition of color. Strictly speaking, color is a visual experience. It is a perception, and therefore the word color refers to human physiological and psychological responses to light. In everyday language, color is associated with words such as red, green, blue, and yellow. Actually, these words refer to only one of three attributes of color—namely hue. The other two attributes are brightness (or lightness) and saturation. To perceive a color, three things are necessary: an object, a light source, and the eye or visual system. See Figure 9-1.

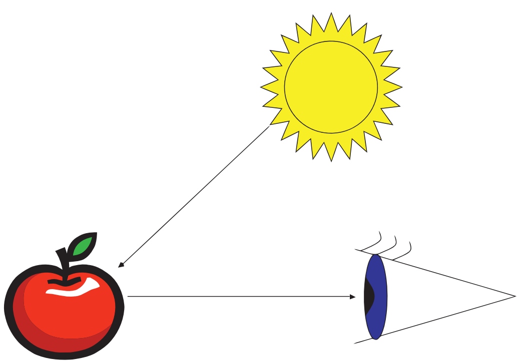


Figure 9-1 Color is a perception that occurs when a light source, an object, and the visual system interact.

Clarity of language is achieved when we distinguish between using color terms to refer to the visual perception of an object and the physical characteristics of the object. For example, it can be argued that we should not refer to a "red" apple as being red. We see it as red because the surface of the apple has physical properties that reflect certain wavelengths and absorb other wavelengths of the white light that illuminates it. If a "red" object is illuminated with "blue" light, most of the light will be absorbed and the object will be perceived as being black. Thus, when we identify an object as being red, we really mean that persons with normal color vision will generally perceive it as being red when it is illuminated with white light and viewed under normal viewing conditions.

Colorant is a general name for colored substances, including pigments and dyes used to alter the color of objects or other materials. The colors we see in color photographs result from mixing three colorants in the photographs: cyan, magenta, and yellow dyes. The purpose of the three dyes, which are present in different proportions in various areas of the photographs, usually is to create the same perception of color as when the original scene is viewed directly—even though a wavelength-by-wavelength comparison of the light entering the eye from the scene and from the photographic reproduction might reveal entirely different compositions. In other words, the photograph is intended to create the illusion that it has faithfully reproduced the reflection characteristics of the original scene, without actually doing so. In a sense we live in two different worlds, the physical world and the psychological world. The physical world lends itself rather easily to measurement. We use

instruments such as thermometers, clocks, and rulers to measure temperature, time, and distance.

Spectrophotometers

The most fundamental physical instrument for measuring color is a spectrophotometer. It is a specialized photometer (light meter), as the name suggests—spectro refers to the fact that the instrument is capable of measuring light of different hues or wavelengths in the color spectrum from blue to red (measurements can also be made of radiation in the infrared and ultraviolet parts of the electromagnetic spectrum with some spectrophotometers). One can think of a color densitometer that measures red, green, and blue densities as a limited spectrophotometer capable of measuring only three broad parts of the color spectrum according to the particular type of red, green, and blue filters used.

A spectrophotometer is a much more sophisticated instrument capable of measuring the density (or transmittance or reflectance) of a given sample at very precise and narrow intervals of color (wavelengths). The intervals are specified in terms of bandwidth. Light, for example, covers a bandwidth of about 300 nm (400 nm to 700 nm). Red, green, and blue light can be thought of as covering a bandwidth of roughly 100 nm each. A spectrophotometer has a dispersing element (prism or diffraction grating) that can separate white light into a full color spectrum. Then, through the arrangement of an optical network of lenses and slits, narrow bandwidths of color 10 nm or less can be isolated and measured after they pass through or are reflected from a sample (see Figure 9-2). This is done at 10-nm intervals over the entire spectrum of colors to be measured.

Spectrophotometers also are used to measure the spectral quality of light emitted by various sources.

Spectrophotometers measure the reflectance or transmittance of color samples wavelength by wavelength throughout the spectrum.

Spectrophotometric Curves

Spectrophotometric curves, such as those shown in Figure 9-3, can then be plotted from the data. The curves provide a contour or envelope that describes the reflection or transmission characteristics of a sample, such

The word "spectrum" resulted from the belief in early times that this phenomenon was a phantom of light or a specter.

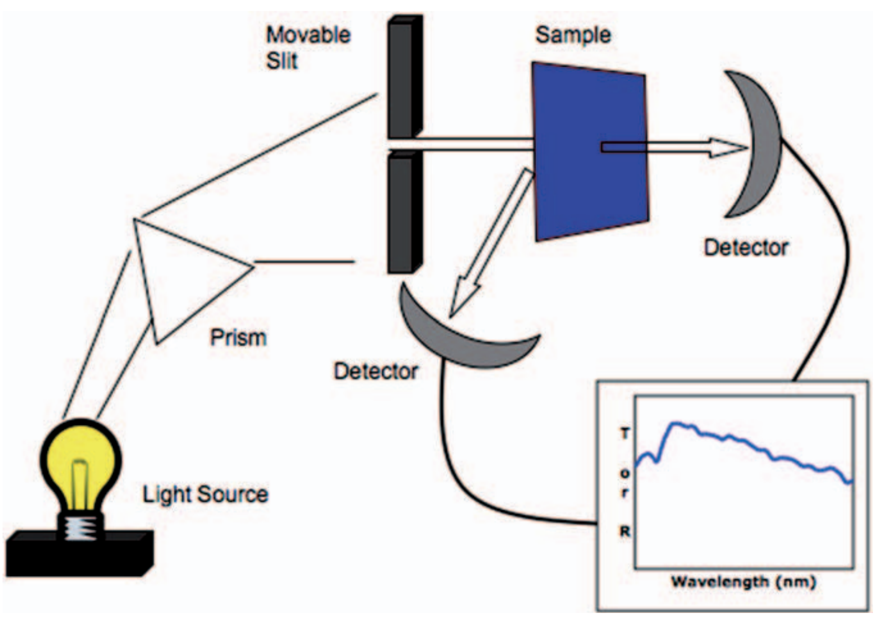


Figure 9-2 A simplified illustration of a spectrophotometer in transmission and reflection modes.

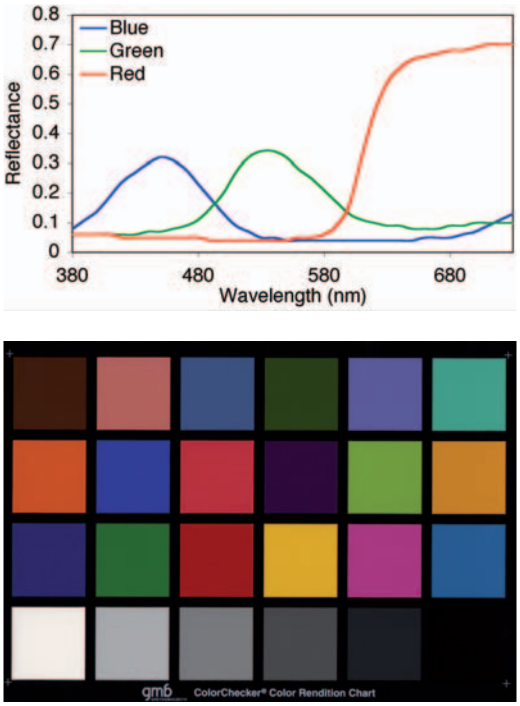


Figure 9-3 Spectral reflectance curves for the red, green, and blue patches of the Gretag MacBeth Color ColorChecker (first three patches in the third row.)

as an image area in a color print. It is important to understand that such curves describe the physical characteristics of the colored samples, not the colors that would be perceived by a person viewing the samples.

The curves of the three-color patches from the Gretag MacBeth ColorChecker show that the red sample has the highest reflectance of the three samples at approximately 0.7. The blue and the green samples have approximately the same peak reflectance around 0.33. Examining the three patches on the ColorChecker, there does not appear to be a great difference in the reflectance or brightness of these three patches. Depending upon how the spectral response is specified, spectrophotometric curves can be referred to as spectral transmittance, spectral reflectance, or spectral density curves.

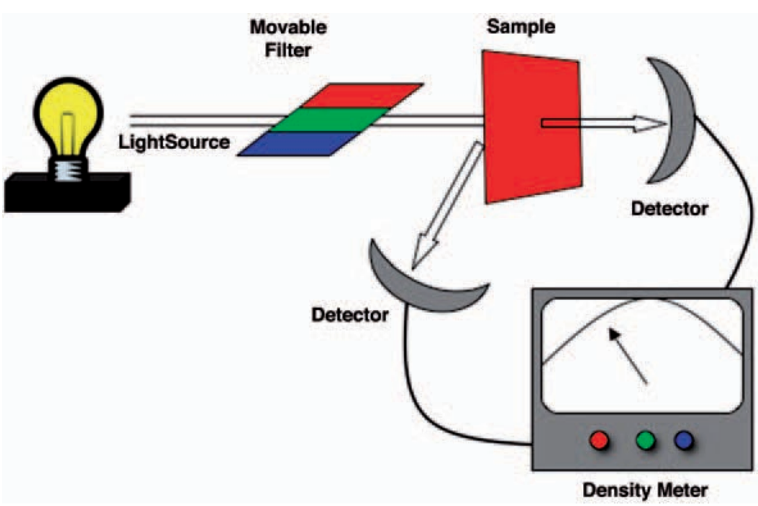


Figure 9-4 A simplified illustration of a color densitometer in transmission and reflection modes.

Color Densitometers

An essential difference between a color densitometer and a spectrophotometer is in the bandwidth of light being used to measure reflectance or transmittance of a color sample. Whereas a spectrophotometer uses a prism or diffraction grating to spread the light and a slit to isolate narrow spectral bands of light ranging between 1 nm and 20 nm, a densitometer uses red, green, and blue filters to isolate broad bands of light of about 50 nm (see Figure 9-4). The result is not a curve showing the spectral transmittance or reflectance of a color sample at each wavelength, such as in Figure 9-3 but simply three numbers, expressed as density (the log of the reciprocal of the transmittance or reflectance). The recommended red, green, and blue filters for use in measuring most color transparencies and prints are the Wratten 92, 93, and 94 filters, with bandwidths of approximately 60 nm, 30 nm, and 35 nm, as shown in Figure 9-5.

Color densitometers can be classified as either visual, if the human eye serves as the receiver, or physical, if some other light-sensitive device such as a photodiode is used. Densitometers can be further classified as direct reading,

if the receiver output indicates the density, or null type, if the receiver indicates when two beams of light are balanced or equal. Visual densitometers are always of the null type based on the equality of light passing through the sample being measured and light passing through an area of known density.

Color Densities

Color densitometers measure the density of a colored layer to broad spectral bands of light as determined by the choice of filters. In photography, color densitometers are used to measure the density of cyan, magenta, and yellow dye layers to red, green, and blue light. Ideally, cyan dye would absorb only red light and transmit blue and green light freely. In practice, cyan dyes also absorb some blue and green light. Therefore, the combined density of the three dye layers in a color transparency would be different if the layers were peeled apart and measured than when they are measured in the normal superimposed position. If all three layers are measured as one unit, the results are called integral color densities. When each layer is measured separately, the results are called analytical color densities.

Integral density measurements are typically used for the control of photographic color processes and to determine the printing times required for color negatives. Analytical densities are used primarily for research and development to improve existing color products and to develop new products. Figure 9-6 shows a spectrophotometric curve (expressed as spectral density) for a typical color film. The three lower curves represent the spectral analytical densities for each layer separately, while the upper curve represents the spectral integral densities of

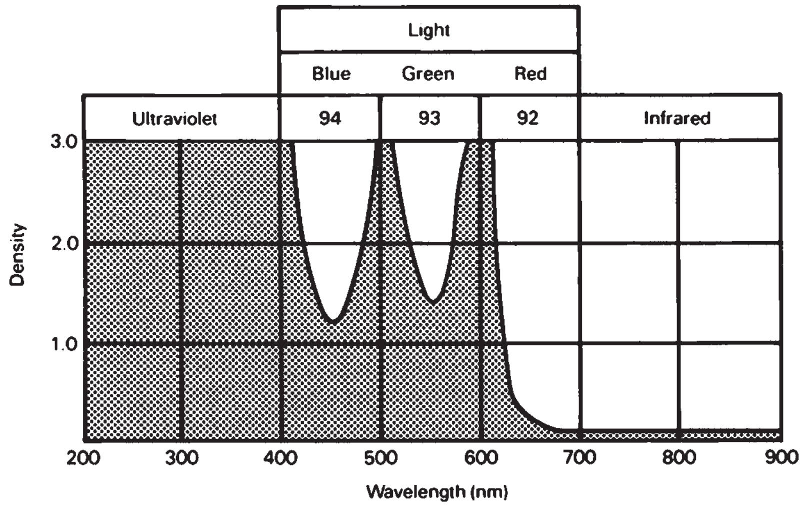


Figure 9-5 Wratten 92, 93, and 94 filters are recommended for color-density measurements of photographic color transparencies and prints. (All gelatin filters absorb UV but transmit IR.)

the cyan, magenta, and yellow layers combined to form a neutral.

Integral densities made with a color densitometer would give three separate values—density to red light (D_r), density to green light (D_g), and density to blue light (D_b). If the bandwidth of the three filters in the densitometer coincided with the three peaks of the upper curve in Figure 9-6,

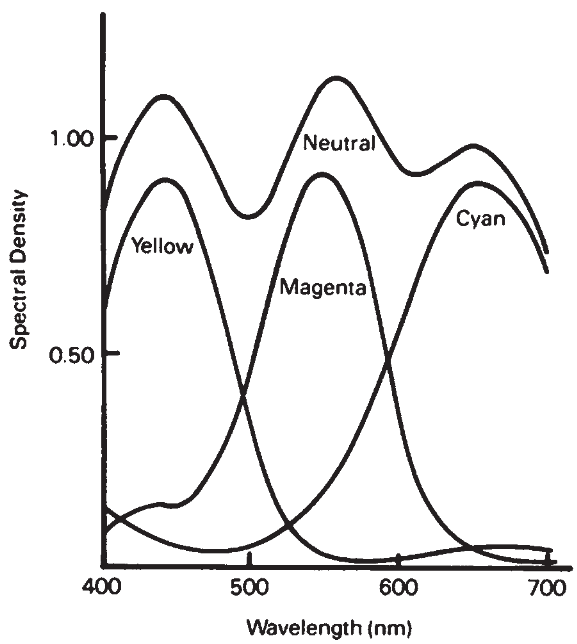


Figure 9-6 Spectrophotometric curves for a visually neutral sample of color reversal film.

one could speculate that D_r would be a little less than 1.0, while D_g and D_b would be higher. The difference between the peak analytical densities and the integral densities at the same wavelengths represents unwanted absorption of blue and green light by the cyan dye, unwanted absorption of red and blue light by the magenta dye, and unwanted absorption of red and green light by the yellow dye.

Color density measurements highly depend upon the choice of red, green, and blue filters used to make the measurements and the spectral sensitivity of the photocell. Even when the same filters and photocell are used, one should not be surprised to discover differences. It is good practice to maintain control charts for color densitometers.

Physical, Psychophysical, and Psychological Measurements

Hue is the name given to a color, such as red or green.

Saturation is the degree that a hue differs from white.

Brightness is how much light an object appears to reflect or emit.

Color analyzers used in color printing darkrooms are essentially color densitometers that indicate the filtration that should produce an appropriate color balance in the print.

Spectrophotometric curves describe the physical reflection or transmission characteristics of a colored object. We use our own perceptual systems, however, to make psychological measurements of hue, saturation, and brightness. Because psychological measurements are personal and subject to great variability, specialized instruments have been developed that provide, under rigidly specified conditions, physical measurements that correlate well with psychological visual perceptions. Such measurements are called psychophysical because they combine both worlds.

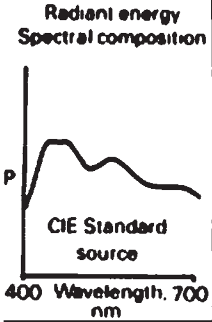
Figure 9-7 provides a comparative listing of terms to describe the attributes of light when the measurements made are physical, psychophysical, or psychological. Thoughtful description of these attributes will distinguish the intended meaning and facilitate clarity. For example, a spectrophotometer will measure the spectral distribution of light reflected from an object or transmitted by an object. This is strictly a physical measurement. An instrument called a colorimeter (to be discussed later) has a response characteristic similar to the human eye and specifies the chromaticity of the spectral distribution. This is a psychophysical measure that describes the quality of color relative to a neutral color in terms of dominant wavelength (hue) and purity (saturation), and allows it to be positioned on a color map (CIE diagram to be discussed later). How that particular chromaticity is sensed by a human observer falls into the realm of psychological measurement and is called chromaticness (or chrominance). Chromaticity and chromaticness represent only two of the three attributes of color; the other is luminance (brightness/ lightness).

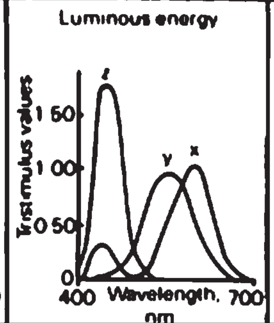
Color, like time and space, is a distinctive property of our daily experiences. The concern of different individuals with color will depend to a large extent upon their chosen professions. A chemist may be concerned with the molecular dye structure of the colorants—a colorimetrist with precise psychophysical measurements and specification—a psychologist with repeatable and predictable psychological measurement—a painter with the esthetics; and a photographer with the esthetics, accuracy of reproduction, archival qualities, and communication of color.

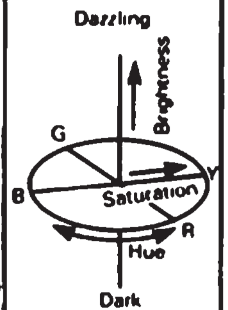
Color Chain

The perception or measurement of color follows a chain of events. There are four major links in the chain. The characteristics and interactions of the first three—light source,

PHYSICS	PSYCHOPHYSICS	PSYCHOLOGY	
Light Source	Source x Eye	Color Perception	
Characteristics of Radiant Energy	Charateristics of Luminous Energy	Attributes of Color	Corresponding Modes of Appearance
Radiant flux	Luminous flux	Brightness	Aperture
Radiance	Luminance		Illuminant
Irradiance	Illuminace		Illumination
Radiant reflectance	Luminous reflectance		Object modes
Radiant transmittance	Luminous transmittance		Surface
			Volume
Spectral distribution	Chromaticity	Chromaticness	Attributes of modes of appearance
(Relative spectral composition, quality)	Dominant wavelength (or complementary)	Hue	1. Brightness (for lightness)
Radiant purity	Purity	Saturation	2. Hue 3. Saturation 4. Size 5. Shape 6. Location 7. Flicker 8. Sparkle 9. Transparency 10. Glossiness 11. Luster







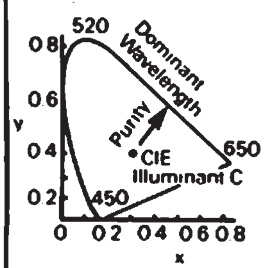


Figure 9-7 Adapted from the system of nomenclature as given by the Committee on Colorimetry of the Optical Society of America 1943. (Sheppard, J., 1958, p. 11.)

Although instruments can measure the physical characteristics of light, the measurements cannot accurately predict the color perceptions that will be produced by the light.

color stimulus, and receiver—determine the response, which can be described in psychological, physical, or psychophysical terms. Some of the terms used to describe the characteristics of the various links are:

1. Light source: illuminant, color temperature, correlated color temperature, spectral energy distribution, tungsten, sunlight, and daylight.
2. Color stimulus: colorant, dye, ink, pigment, color object, spectral reflectance or transmittance.
3. Receiver: human eye, photocell, photographic film.
4. Response: Munsell system (psychological), spectrograph (physical), CIE system (psychophysical).

Color Mode

The characteristics of the color stimuli can be further expanded to include the particular mode of appearance or context in which colors are experienced. There are five such modes generally recognized, which influence the response

Figure 9-8 Five modes of color perception, (A) surface, (B) volume, (C) aperture, (D) illumination color, and (E) illuminant color.

Computers can generate and display over one million physically different colors.

One of the problems in making water and sky look natural in a color print is that the print can only represent volume color and aperture color as surface color.

to the color stimuli—surface, volume, aperture, illumination, and illuminant. When photographing color, it helps to recognize and distinguish between these various modes (see Figure 9-8).

The most common is the surface mode or surface color, which refers to light reflected from and modified by a surface. It is seen as belonging to a surface. Examples are painted walls, color photographs, fruits, vegetables, human skin, and all such objects that present reflecting surfaces.

Volume color refers to color perceived when looking into or through a uniformly transparent substance such as a liquid. Examples would be the bluish color of water in a swimming pool, yellowish color of cooking oil in a bottle, and yellowish color of lemonade. A liquid filter used to change color temperature is yet another example. The strength of the volume color is determined by the concentration of the liquid and the thickness or depth.

Aperture color refers to color perceived in space and not recognizable as an object. Examples include the bluish color of the sky and the reddish color of a sunset or sunrise, which seem to fill the “emptiness” above us. Light seen in an opening, such as the color lights projected into an aperture of a colorimeter for color matching, is a prime example of an aperture color mode. (Aperture color is sometimes referred to as film color, which can be confusing to a photographer.)

Illumination color refers to the perceived color of light falling on an object. A familiar example in color photography occurs when we are taking photographs outdoors under sunlight conditions and we find that the shadows in the white snow (or on light sand or concrete) tend to have a bluish cast. This results from fill light from the blue sky, which casts a diffuse blue light over the entire landscape. Such bluish shadows are recorded objectively by light sensitive material as illumination color, but rarely by the eyes, which tend to compensate.

We may not perceive them as such, but the colors we see reflected from a movie screen can be thought of as illumination colors. A projector has a white light source that is modified by the color film in the projector. The various colors of light passing through the film fall on a white screen surface and are reflected. We could, but generally do not, see them as illumination colors. In a studio setting, we usually use white lights to obtain surface colors. If we used a warm (reddish) light to represent light from a fireplace, however, the colors would be modified. We would then attribute the altered appearance of the color objects to illumination color.

Illuminant color is distinguished from illumination color in that it is the color of the light source viewed directly. Instead of looking at the illumination color on the movie screen, we could turn around and look directly at the projector and the colors of light passing through the lens. More common experiences of illuminant colors

are red, green, and yellow traffic lights, Christmas tree lights, and neon lights. Another example of illuminant color is the viewing of a television picture computer display. The television screen consists of thousands of dots of red, green, and blue phosphors that emit light as they are energized. When we view color pictures or color graphics on a television screen, we are looking directly at the light source. This system of color reproduction is uniquely different from a photographic system. (When working with video color systems it is important to realize that there is a decided difference between displaying pictures of three-dimensional objects on a television screen and using a computer to generate pictures and graphics on a television screen. Important to our perception of color are texture and line, which are often inadequate with computer-generated graphics.)

Primary Colors

Surprisingly enough, the minimum number of colors needed to form most other colors, by additive mixing, is three. They must be independent of each other—that is, two of the three colors when mixed must not form the third color. For subtractive systems of color, such as photography and printing, the primaries are called cyan (blue-green), magenta (blue-red), and yellow (red-green) colorants (inks, pigments, dyes). See Figure 9-9.

In additive systems of color, the primaries are red, green, and blue (Figure 9-9). Television is an additive system, which uses small dots of red, green, and blue phosphors that are too small to resolve as separate dots, although they can be seen with a magnifier. (Avoid doing this for any length of time since television tubes emit some potentially harmful radiation.) An early example of an additive system used to produce photographic color transparencies is Dufaycolor, which used a mosaic of minute red, green, and blue filters and was introduced in 1934.

Since the subtractive color primaries—cyan, magenta, and yellow—are complementary to the additive color primaries—red, green and blue—they are sometimes referred to as minus-red, minus-green, minus-blue. In color printing, it is especially helpful to think of cyan, magenta, and yellow filters in this way. It is also helpful to remember that a neutral can be formed by combining complementary colors (see Figure 9-10).

Although all color films contain cyan, magenta, and yellow dyes, they will not produce identical color images.

Neutrals are sometimes called achromatic colors. This expression is an oxymoron—a contradiction of terms. White, gray, and black are colors that have lightness but no hue or saturation.

"Color possesses me. I don't have to pursue it. It will possess me always . . . Color and I are one."
—Paul Klee

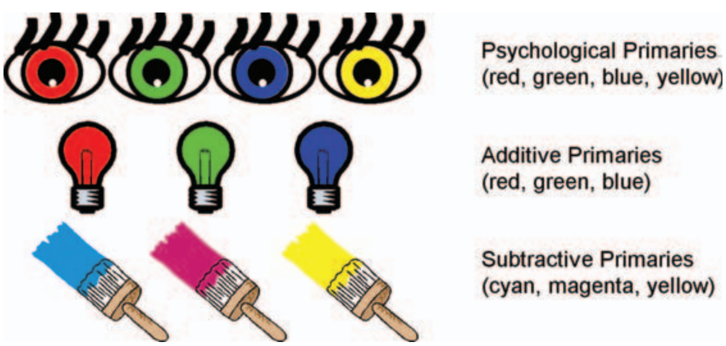


Figure 9-9 The psychological primaries are perceived as distinct from any other colors. The additive primaries of light can be added together to create any other color and the subtractive primaries are colorants that must be superimposed on each other to form most colors.

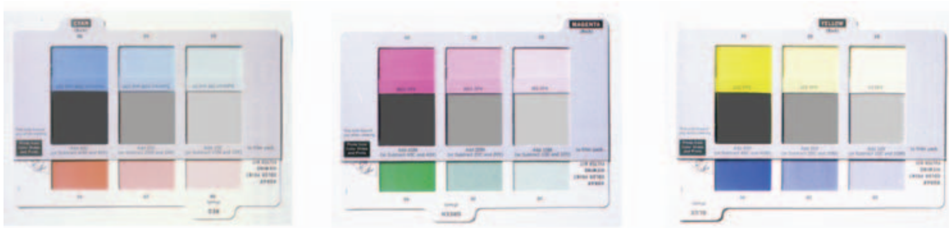


Figure 9-10 When mixed in proper proportions, complementary colors form neutral or near neutrals.

Although the selection of the three primary colors for the subtractive as well as additive systems is somewhat arbitrary, the choice is usually based on a number of factors—ability to produce the colorants, ability of the colorants to reproduce the greatest number of secondary colors, stability, availability, cost, and convenience.

Color Attributes

When describing the colors we experience, we use such familiar words as red, green, yellow, orange, and blue. Often though just the color name blue is not enough to describe what we are seeing. We will add to that, for example, using terms such as darker or lighter, stronger or weaker, or we will go one step further adding other descriptors such as sky blue, royal blue, or navy blue to further describe a color. This is because colors have three distinct attributes: hue, saturation, and brightness (or lightness). When we say lipstick is red, we are referring to hue. Saturation describes how strong or intense the red hue is, and brightness or lightness how light or dark the red hue is (see Figure 9-11). We will see later that the specific terms used to describe these attributes distinguish the different systems for specifying color.

Neutrals

When mixed in the proper proportions, complementary colors produce neutral colors. Colors such as cyan and red, magenta and green, yellow and blue will, when mixed, form neutrals having various levels of lightness or brightness (see Figure 9-10). Neutrals are distinguished from other colors in that they have no hue or saturation, so they are sometimes referred to as *achromatic colors*. A scale of such neutrals ranges from black to white and is called a *gray scale*. It is wrong, as many of us have been taught in early schooling, to think of black or grays as the absence of color. Grays appear neutral because they do not alter the color balance of the incident white light illumination. They appear dark or black when little light reaches the eye, and they appear light or white when much light reaches the eye.

One of the most critical tests of a photographic color material or a digital sensor is its ability to reproduce a

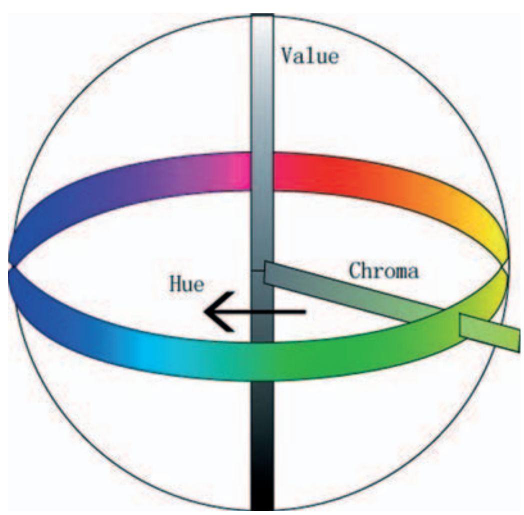


Figure 9-11 The three attributes of color: hue, saturation (chroma), and brightness (lightness or value).

scale of neutral colors. Small variations in color balance can be detected more easily with neutral colors than with saturated colors. To the eye, a neutral color is either neutral or not, whereas a color such as red can be modified considerably by the addition of blue (magenta-red) or yellow (orange-red) and still be accepted as red.

In testing the ability of a color film or paper to reproduce neutrals note that the results often depend more upon the user than the manufacturer. Regardless of how good the product is, if it is improperly stored, exposed to the wrong color temperature light or to mixed lighting, improperly processed, or viewed under poor lighting conditions, the photographer cannot expect quality results.

Color-Vision Theory

As early as 1666, a 23-year-old instructor at Cambridge University, Sir Isaac Newton, demonstrated that white sunlight is made up of all colors of light. He did this by passing sunlight through a prism to create a spectrum of colors. This demonstration gave visual evidence of how light can be separated into different colors. It was not until 1704, however, that Newton put forth a hypothesis to explain the process by which we see colors. He speculated that the retina contains innumerable light receptors, each of which responds to a specific color stimulus. Thomas Young rejected this nearly a hundred years later, in 1801. In a terse 300-word statement, Young hypothesized that there are only three different kinds of light receptors in the retina, each responding to one color of light—red, green, or blue. His theory was in turn rejected and ignored by his contemporaries. Some fifty years later, in 1850, Young's theory of red, green, and blue color receptors in the retina was rediscovered by James Clerk Maxwell and Herman von Helmholtz.

Although many theories attempt to explain our response to color, many unanswered questions remain. Some theories, however, are more useful than others. The oldest, most efficient, and most persistent theory of color vision is the Young-Helmholtz three-component theory. This theory postulates that there are three kinds of receptors in the retina that react selectively. One can think of these as red or long-wave, green or mid-wave, and blue or short-wave receptors that somehow combine in our visual system and produce the perception of other colors.

Some unanswerable questions have been raised regarding this three-color theory for human vision. For example, the eye will distinguish not three but four fundamental or primary colors—colors that are distinct and have no trace of other colors. The colors are red, yellow, green, and blue and are called the *psychological primaries*. The Young-Helmholtz three-color theory does not account for the psychological primaries, where as the Hering theory of color vision, referred to as the opponent color theory, does.

The Hering opponent colors theory is a more complex. Whereas the Young-Helmholtz theory is based on three-color stimuli, the Hering theory is based on the response to pairs of color stimuli. It assumes that there are six basic independent colors (red, yellow, green, blue, white, and black). Rather than postulating special and separate receptors for the six colors, Hering proposed that the light absorbed by the red, green, and blue sensitive receptors in the retina starts a flow of activity in the visual system. Somehow this flow is channeled into three pairs of processes with the two components of each opposing one

another (opponents). The opposing pairs are blue-yellow, green-red, and white-black. For example, a color may look bluish or yellowish but never both at the same time. Blue would oppose and cancel yellow, and vice versa.

A variation on the Hering theory that provides for quantification is the Hurvich-Jameson quantitative opponent-colors theory. This theory assumes a two-stage process. The first stage is the excitation stage, located in the cones of the retina and consisting of four light-receiving cells that contain combinations of three photo chemicals. The second stage is an associated response stage located beyond the retina in the visual nerve center. It has three paired-opponent processes: blue-yellow, green-red, and white-black. This opponent-response theory represents differences in the neural response to the stimulation that originated when the cones in the retina were excited. A single nerve transmits two different messages by one of the pairs of opponent colors raising the neural firing rate above the normal rate (excitation) and the other lowering the firing rate below the normal rate (inhibition).

When making color prints, photographers sometimes use color matching to determine the correct filtration and exposure.

Viewing color television pictures, composed of red, green, and blue primary colors, is an example of spatial color integration.

Color Specification Systems

Five different modes of perceiving color were mentioned earlier. The most common mode is object color or surface color, since it is the light reflected from the surfaces of objects that we normally see—a red tomato, green grass, blue shirt, skin colors, and so on. Three are basically three types of systems or methods for describing or specifying a color.

The first method is defined by color mixing. The Pantone Matching System®[1] is an example of this type of specification system. In this type of system, the observer is provided with a discrete set of color sample chips to choose from. When a selection is made, information from that chip is used to create that color. That information would include information on the percentages of different ink, pigments, or paints needed to produce that color chip.

The second method for object-color specification is a color-order system and is defined by perceptions. The Munsell Color System, which consists of hundreds of samples, is a color-order system. The color chips are spaced so that they appear to have uniform intervals of hue, saturation, and lightness. This requires judgment by a standard observer under a standard set of viewing conditions. The Munsell Color System is very useful to practicing photographers, artists, and designers.

The last system is defined by matching perceptions to a standardized set of lights. An example here is the CIE Color System, that specifies color in terms of three parameters, Y,x,y and which are calculated based on the visual response of a standard observer, the spectral power distribution of the light source and the spectral reflectance of the sample. The CIE system is used extensively in color management systems and will be discuss in detail later in this chapter.

Munsell System of Color Specification

Albert Henry Munsell was a painter and an art teacher (Figure 9-12). He found that communicating with his

[1] Pantone® is Pantone, Inc.'s check-standard trademark for color reproduction and color reproduction material.

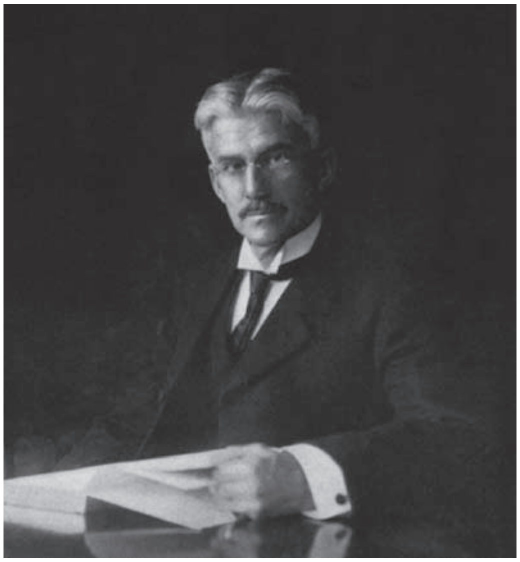


Figure 9-12 Albert Henry Munsell.

students about color was frustrating at times.

In 1905 Munsell published his first edition of *A Color Notation*, and in 1915 he published the *Atlas of the Munsell Color System*. The Munsell System for color identification was one of the earliest attempts to create an accurate system to describe color numerically. One of the Munsell system's strengths is that it provides a common international notation for color in which a person first identifies a color visually (non-verbally) and then uses language to describe it and communicate it. In order to accomplish this, Munsell had to first prepare a large variety (gamut) of painted color chips. Imagine hundreds of such chips having different hues, which Munsell described as the "name of the color"; different values, which he described as "the lightness of color . . . that quality by which we distinguish a light color from a dark one"; and chroma, which is "the strength of a color . . . that quality by which we distinguish a strong color from a weak one; the degree of departure of a color sensation from that of a white or gray; the intensity of a distinctive hue; color intensity."

In sorting out the gamut of color chips, they are first grouped by hue (red, yellow, green, blue, and purple and the in between hues). Then for each grouping of hue they would be arranged according to their values of lightness to darkness. A red hue grouping, for example, would be arranged so that all the red chips increased in lightness from light to dark. The final and more difficult arrangement would be to group all of the chips having the same hue and lightness according to their color intensity or chroma. On one end would be red chips that are near neutral, on the opposite end would be a red chip that would be described as intense or vibrant red or one that was a highly saturated red.

This type of ordering is essentially what Munsell did, with some refinement—the most important refinement being that he ordered the colored chips so that the interval between adjoining chips would be visually equal in hue, value, and chroma, quite a monumental task. Once this visual structuring was completed, he had to communicate it to others so they could also visualize the arrangement and use a common language to describe the colors. Since color has three attributes (hue, value, chroma), it occupies a three-dimensional space or volume. Munsell described this concretely in terms of a color tree. "The Munsell color tree has a vertical trunk that represents a scale of values, branches that represent different hues, and leaves extending along the branches that represent chromas. The hues change as one walks around the tree, the values increase as one climbs up the tree, and the chromas increase as one moves out along the branches" (see Figure 9-13).

A more abstract representation of this color system is shown in Figure 9-14. The trunk of the tree, representing

The Munsell System was developed so the difference between adjoining chips would be visually equal in hue, value and chroma.

"Music is equipped with a system by which it defines sound in terms of its pitch, intensity, and duration, without allusion to the endless varying sounds of nature. So should color be supplied with an appropriate system." —Albert Munsell

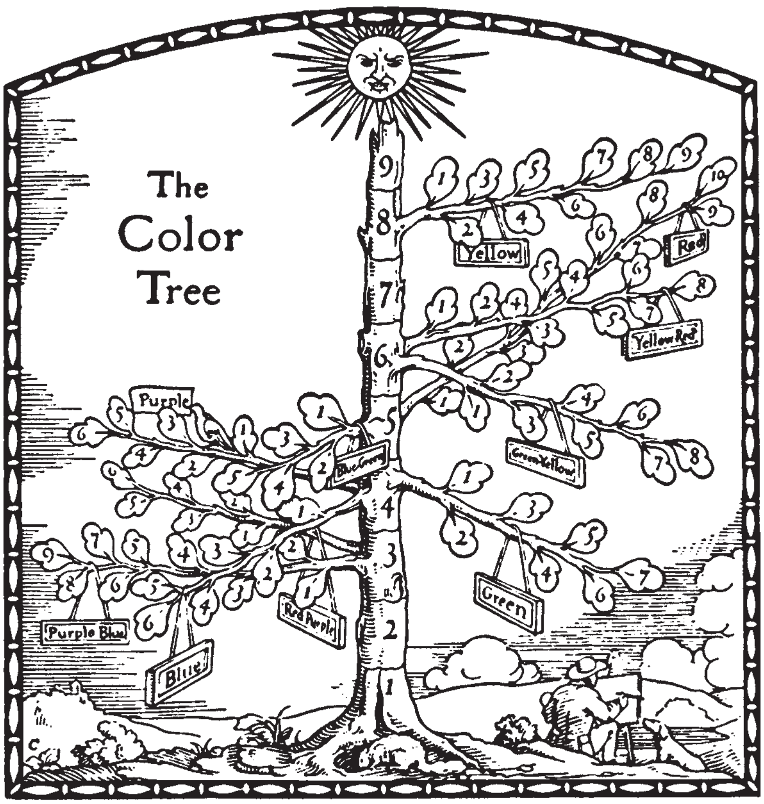


Figure 9-13 The Munsell color tree. (From Munsell, *A Grammar of Color*, edited by Faber Birren, ©1969 by Litton Educational Publishing, Inc. Reprinted by permission of Van Nostrand-Reinhold Co.)

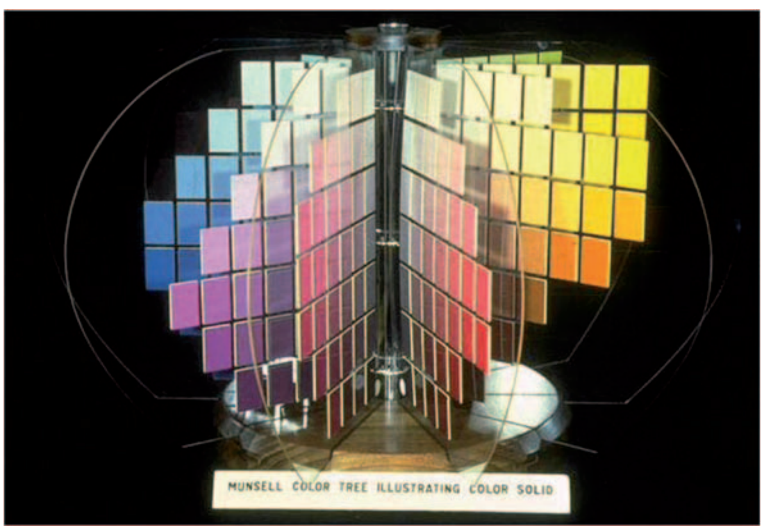


Figure 9-14 The Munsell color tree contains 10 hue charts on clear plastic leaves.

values from black to white, is now the center post of a color sphere; the branches representing the hues are now vertical sheets, each holding chips of a different hue, attached to the center post; and the leaves across each branch now become chips of the same

Figure 9-15 Hue symbols and their placement in the Munsell system.

hue and value but different chromas, extending from the center post outward. Hue changes as one circles the Munsell color sphere, value increases vertically, and chroma increases from the center post outward.

The three attributes of color (hue, value, and chroma) are visually represented in the Munsell tree as a color space or volume. The overall shape of the color space is not symmetrical. This is because the range of chromas is not the same for all hues. In the extreme it is possible to have a yellow hue of high value and high chroma but not one of low value and high chroma. Similarly, a blue hue of high value and high chroma is not attainable. The three-dimensional asymmetrical color solid represents colorants now available, not including fluorescent colors. The Munsell space is expanded as new colorant become available.

Of the one hundred hues that can be represented in the Munsell system, a select sample of ten are actually shown. The others would fall in between, and all one hundred hues would be equally spaced in terms of visual differences as illustrated in Figure 9-15. The five basic hues are red, yellow, green, blue, and purple.

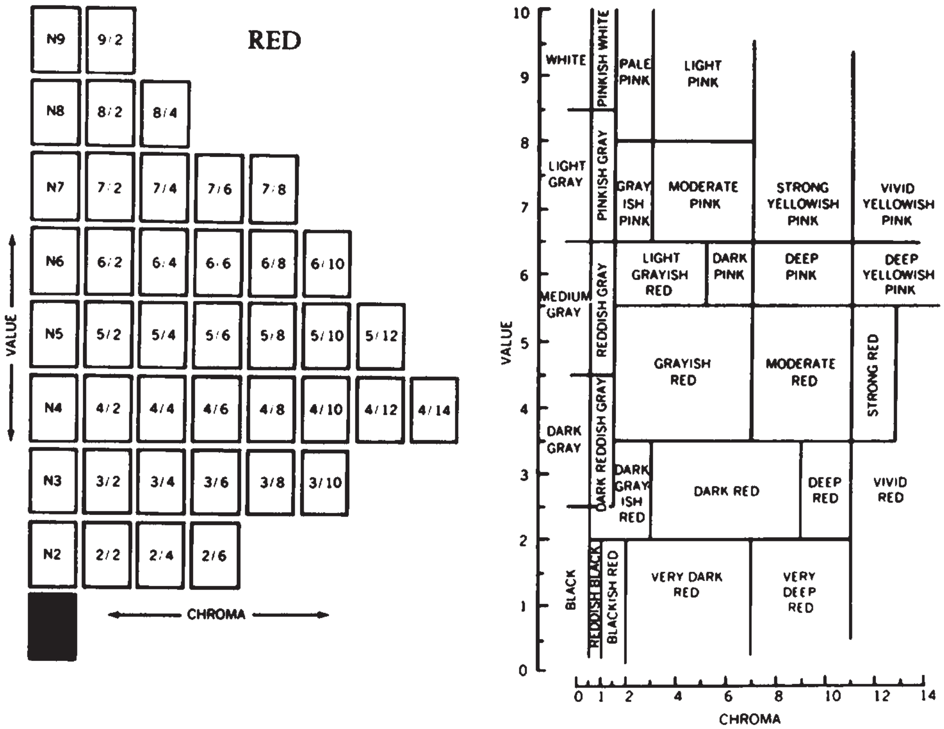


Figure 9-16 Method for converting Munsell notations to color names using the ISCC-NBS (Inter-Society Color Council and National Bureau of Standards) Method of Designating Colors, and a Dictionary of Color Names. (Available as circular 553 from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.)

Figure 9-15 shows how the ten major hue names can be used for qualitative notation. The one hundred numbers in the outer circle provide more precise notation. The numbers make it easy to use the Munsell system for statistical work, cataloging, and computer programming. The combination of numerals with hue initials is considered the most descriptive form of designation. This combination is shown in the inner circle: 5R, 7.5R, 10R, 2.5YR, 5YR, 7.5YR, 10YR, etc. The Munsell Book of Color shows the actual colors of these forty constant hues.

For a particular hue, say one of the ten major hues represented in the Munsell tree, there are a number of different values and chromas, and therefore different colors, of that hue. Imagine the 5 Red hue segment removed from the tree. The 5R notation designates that this hue is midway between a 5RP and a 5YR on the hue circle. The 5R by itself designates only the particular hue, not the color. As indicated in Figure 9-16, the 5R hue can be further specified in terms of value and chroma numbers or described in terms agreed upon by the Inter-Society Color Council and the National Bureau of Standards (the ISCC-NBS).

In the Munsell system, color is specified in the alphanumeric sequence Hue Value/ Chroma (H V/C). For example, a 5R hue with a value of 8 and a chroma of 4 would be called a Light Pink and designated 5R 8/4 or simply R 8/4 (for hues having positions other than 5 on the hue circle the position must be indicated—for example, 3R 8/4). R 5/12 translates to a strong red having a value of 5 and a chroma of 12. At the extreme left of the diagrams (center of the Munsell tree), the colors are neutral and are so represented. The notation for a neutral (achromatic) color is written NV/; for a middle gray (18% gray)

"Hue is the name of a color. Value is the lightness of a color. Chroma is the strength of a color." —Albert Munsell

In other systems, chroma is called saturation, and value is called lightness or brightness.

"Viewing of color in a particular situation is, at best, a peculiar mixture of attention, intention, and memory." —Ralph Evans

Although the spectrum is commonly divided into regions having seven different hue names (red, orange, yellow, green, cyan, blue, and violet), the Munsell system identifies 10 major hues and 100 distinguishable hues.

the notation is N5/. Since the chroma is zero, it is usually omitted but could be included (N 5/0). (For those interested in Zone System notation a black, Zone 0, would be about N1/; a Zone V gray, N 5/; and a Zone IX white, N 9/.)

Near neutrals having chromas less than /0.3 are usually treated as neutrals. If more precision is needed, the form N V/(H,C) is used (H would be represented by one of the 10 select hues). For example, a light gray that is slightly yellowish might be noted as N 8/Y,0.2 or, using the regular H V/C form, Y 8/0.2. The form N V/0 can be reserved for absolute neutrals.

Pantone® System of Color Specification

The Pantone Matching System® (Figure 9-17) is an object-color system widely used in the graphic arts industry. It differs from the Munsell system in that it is not based on equal visual differences in color, and in that the colorants used are inks common to graphic arts printing. Using colorants similar to those used for printing provides a closer match between the colors selected and specified by the client and the colors produced by the printer. The system comprises more than 500 standard Pantone® colors by blending various proportions of eight basic chromatic colors, plus black and transparent white. To produce a Pantone® 292 color similar to a Munsell 5PB 5/10, for example, would require 2 parts Pantone® Reflex Blue, 2 parts Pantone® Process Blue, and 12 parts transparent white. The reproduction of a gray card can be specified by matching it first to a Pantone® color such as Pantone® 424 and then giving that information to the printer. The printer knows that the gray card color can be reproduced with an ink mixture of 3 parts Pantone® Black, 1 part Pantone® Reflex Blue, and 12 parts transparent white.

Figure 9-17 Pantone Matching System.

The colors used in Figure 9-17 were chosen by the authors from the Pantone® Color Formula Guide. The Pantone numerical designation for each color specified was communicated to the book's graphic designer, who in turn used the same notation to communicate the desired colors to the printer. In this way, author, designer, and printer shared a common color language, which facilitated communication and reduced error. Any standard system of color notation provides this. In communicating colors to others, however, it is essential to know which system they are using. One shortfall of the Pantone system is not all colors are available. Only those in Pantone Sample book can be used. When converting a photographic image to a Pantone image, the resulting image will not be an exact color match for this reason. (For more information on Pantone® Matching System write to Pantone, Inc., 55 Knickerbocker Road, Moonachie, NJ 07074.)

CIE System of Color Specification

The letters CIE stand for Commission Internationale de l'Eclairage (The International Commission on Illumination).

In 1931 the CIE system of color specification became an international standard for colorimetry.

Color specification with the CIE system differs from that of the Munsell in that a mixture of red, green, and blue light is used to match a given sample rather than the selection of a color chip. The Munsell system is based on appearance, whereas the CIE system is based on stimulus-synthesis (the additive mixture of three color primaries). Both systems have advantages, and specifying a color sample with one system allows conversion and notation to the other. The obvious advantage of the Munsell system is its simplicity and its directness. The selection of one of the color chips provides a color and color notation directly in terms of hue, value, and chroma (H V/C). It is a physical match easily made and easily understood. The CIE system is somewhat abstract and is based on mathematical conventions. It requires instrumentation but has the advantage that any color can be matched, numerically specified, and positioned on a CIE diagram or map. The CIE system provides psychophysical measurements of color, whereas the Munsell system, based on color appearance, provides psychological or perceptual measures. However, the CIE color specification system is used in color management exclusively.

The CIE color system specifies colors in terms of three parameters, Y which is the luminance term, and x and y which are chromaticity coordinates. The x and y terms are derived from tristimulus value (XYZ) of the sample in question. Tristimulus values are determined by integrating the spectral power distribution of the light source the color sample will be viewed under, the spectral reflectance of the color sample and the response of the standard observer. (The CIE has determined the response of the standard observer through well documented experiments). Once the tristimulus values are obtained, the chromicity coordinates can be calculated. (See Appendix D for these calculations). One advantage of this system is that any color can be quantified. A drawback is that it is not a visual system, meaning that given a set of coordinates it is not easy to determine the exact color.

CIE Chromaticity Map

Chromaticity describes two attributes of color—hue and chroma. These two qualities, called dominant wavelength and purity in the CIE system, are plotted on a horseshoe-shaped map, shown in Figure 9-18. Around the periphery of the curved section are wavelengths of light scaled from 380 to 770 nm. The x and y axes are used to plot the position of the chrominance of a particular color. The color is always plotted relative to a specific light source. In this example, the daylight source is located in the lower middle of the

Munsell notations can be converted to CIE notations and vice versa.

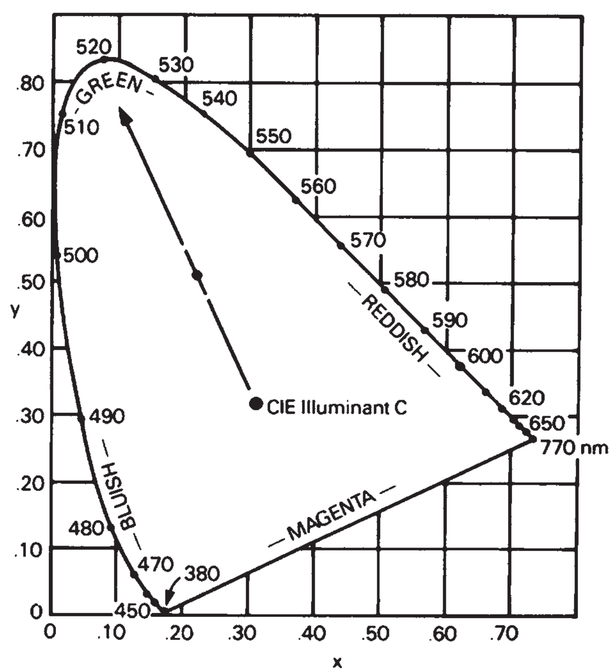


Figure 9-18 Chromaticity plot for a green filter relative to a daylight source.

map, where it serves as a neutral reference point. A green filter is identified by the coordinates $x = 0.22$ and $y = 0.52$. Not shown is the luminance (brightness) of the green. This value is obtained separately from the data used to calculate the x and y coordinates. The farther a color plots from the reference neutral, the greater the purity (chroma). The dominant wavelength (hue) is determined by drawing a line from the reference point through the plotted point to the curved wavelength line. This green filter has a dominant wavelength of 520 nm.

Non-Uniform Color Space

Whereas the CIE 1931 chromaticity diagram in Figure 9-18 provides a convenient mapping space for displaying x,y chromaticity coordinates, color differences displayed by these coordinates unfortunately are not distributed uniformly. Similar color differences between two samples of a reddish or bluish color would be compressed, whereas the same visual difference greenish colors would be expanded in the diagram.

This non-uniformity of plotted color differences was reported in the research done by David MacAdam in 1942. He used a large number of color difference pairs to determine how much of a color change, in any direction, could be made before an observer would perceive a just noticeable difference (JND). In doing so, he found that the variabilities in JNDs were different for each color and that plots of these variability boundaries formed similar elliptical shapes, but were of significantly different sizes. These experimental results helped describe the perceptual nonuniformity of the 1931 CIEXYZ chromaticity diagram, and are known as the MacAdam ellipses.

Uniform Color Space (CIELAB)

In 1976, the CIE recommended the use of a more uniform color difference formula and related color space. They designated CIE L*a*b* (CIELAB) to provide better correlation between visual and measured color differences. The use of CIELAB provided a significant improvement over the nonuniformity of CIE tristimulus space by deriving metrics that correlate to perceptions of color. CIELAB, based on a simple color vision model, can adjust for changes in the color and amount of illumination, signal compression, and opponent signal processing. The CIELAB color space does not have a chromaticity diagram associated with it because of its exponential non-linear derivation from CIE tristimulus space, but a three-dimensional color space can be constructed with L* as the vertical axis, and a* and b* occupying horizontal planes.

The L* value represents luminance and can range from 0 (black) to 100 (white). The a* value represents the redness-greenness of the sample. The b* value represents the yellowness-blueness of the sample. There is not a numerical limit on either the a* or b* value and they can be either positive or negative in value. It is customary to plot only the a* and b* values which results in a two dimensional graph. Color gamut comparisons are easily constructed using the ±a*(redness-greenness), and ±b*(yellowness-blueness) horizontal opponent measurement planes (see Figure 9-19).

Specifying color in terms of CIELAB provides a means for various color specification systems being used in digital photography to "speak" to one another across media components. Regardless of what platform (type of computer) being used—monitor, scanner,

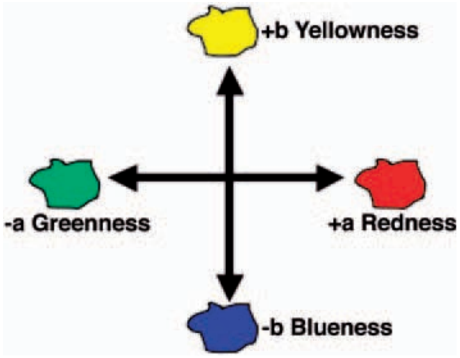


Figure 9-19 a* versus b* plot in CIALAB space.

printer, etc.—and how the colors are being specified, all can feed into a CIELAB-based device-independent reference color space, which allows conversions to be compatible across all existing components of a digital color reproduction system. CIELAB's L* and a*,b* component performance as a simple color appearance model makes it useful in color management systems; however, due to its still not-perfect uniformity, some software vendors prefer to implement their own color space configurations based around CIEXYZ tristimulus values.

Further research in color appearance models are providing experimental and application opportunities in areas such as colorant interactions, sample surface properties, and correlation between physical measurements and visual assessments of color differences both in the fields of color image reproduction and the manufacture of all colored products.[1]

[1] *The Focal Encyclopedia of Photography*, 3rd ed., s.v. "colorimetry." Giorgianni, E. and T. Madden. *Digital Color Management: Encoding Solutions*, Reading, MA: 1977; "COLOR Research and Application," *The Journal of Color Science*, John Wiley & Sons, New York, www interscience.wiley.com; The Munsell Color Science Laboratory at Rochester Institute of Technology, Rochester, New York, 14623, http://www.cis.rit.edu:80/people/faculty/fairchild/ CAM.html

REVIEW QUESTIONS

1. The most appropriate definition of color from the following choices is that color . . .
   A. is the wavelength attribute of light
   B. is the attribute of light associated with names such as red, green, and blue
   C. is the quality of all light that is not white
   D. is a perceptual response to light
2. With respect to the relationship of pigments, dyes, and colorants, all . . .
   A. colorants are dyes
   B. pigments are colorants
   C. dyes are pigments
   D. colorants are pigments
3. Of the light response systems listed, the one that is most similar to a spectrophotometer in principle is . . .
   A. an exposure meter
   B. the human eye
   C. a color densitometer
   D. black-and-white panchromatic film
   E. color film
4. In addition to the color of light that cyan dyes are supposed to absorb, they also absorb considerable . . .
   A. red light and green light
   B. red light and blue light
   C. blue light and green light
5. The mode of the blue seen in blue sky on a clear day is classified as . . .
   A. surface mode
   B. volume mode
   C. aperture mode
   D. illumination mode
   E. illuminant mode
6. White, gray, and black are . . .
   A. chromatic colors
   B. subtractive primary colors
   C. not colors
   D. neutral colors
7. The Munsell term value corresponds to the more general term . . .
   A. color
   B. lightness
   C. saturation

D. harmony
E. darkness

8. The five principal hues in the Munsell system are . . .

A. red, green, blue, yellow, and gray
B. cyan, magenta, yellow, white, and black
C. yellow, red, green, blue, and cyan
D. red, green, blue, yellow, and purple

9. A color designated as 5R 8/2 is a . . .

A. light red
B. dark red
C. medium value red

chapter

10 Color Management

Photograph by David Kelbe, Imaging Science student, Rochester Institute of Technology.

What Is CM?

Color Management (CM) has been going on for as long as color printing paper and color slide film have been available. For instance, a photographer would find a particular batch of emulsion printed a bit on the magenta side and would adjust the printing color balance until that batch of emulsion was finished. CM accomplishes the same thing, however the problem has gotten much more complicated.

In photography today, your digital camera may communicate with your monitor or your printer directly. Creating an image on your computer means your monitor has to communicate with your printer. This seems like a manageable problem as illustrated in Figure 10-1. The relationships between the camera and the monitor, the monitor and the printer, and the camera and the printer have to be defined. This is a system with only three possible relationships.

In the world of digital photography, it is rare that these are the only three devices involved. Perhaps you send an image to a customer electronically. That customer then shares the image with their staff. Your camera now needs to communicate with monitors that you have never seen. That same customer then prints the image on a local printer in their office and sends it to the production department to be printed on a large-format printer. The same digital image could look different when it is viewed on different monitors or printed to different printers. The problem now

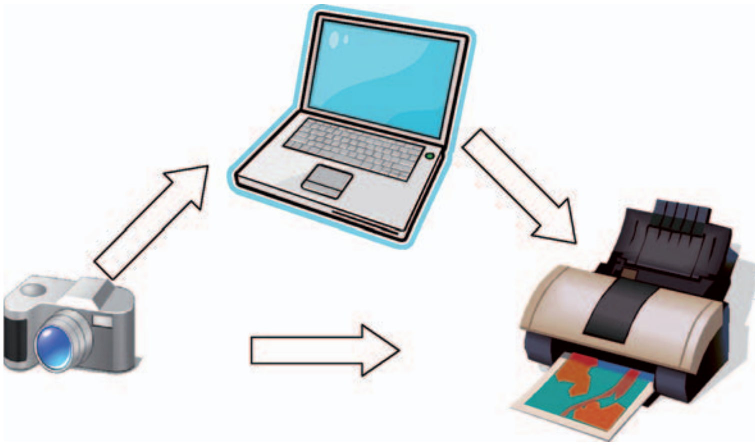


Figure 10-1 Managing color in a system.

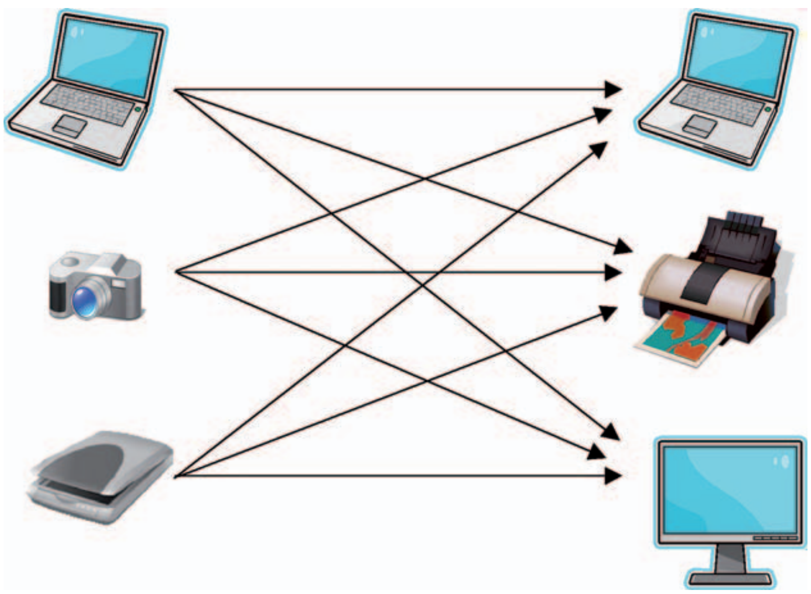


Figure 10-2 The problem of defining a relationship between multiple devices.

becomes bigger, as illustrated in Figure 10-2. Color management is the solution to this problem.

The International Color Consortium (ICC) is the governing body for color management.

What Is Color Management?

In the world of digital imaging systems, color management is the conversion between the representations of color on different devices. These devices can include digital cameras, image scanners, monitors, LCD and plasma television screens, printers, offset presses, and projectors. The goal of color management is to assist in achieving the same appearance of an image on all of these devices. This of course depends on the ability of the devices to produce similar color gamuts. When they can't, color management assists in producing the best compromise of color representation. This is achieved through the use of ICC profiles. ICC profiles are created using a standard common format so that devices made by different manufacturers are compatible with each other.

Who Governs Color Management?

Before going further, we should discuss the background of color management and who governs the standard. The International Color Consortium[1] (ICC) is the governing body in the field of color management. The ICC was founded in 1993 and is the group that oversees the field of color management and maintains the ICC profile specification. The ICC's mission is to promote the use and the adoption of open, vendor-neutral, cross-platform color management systems.

The nine founding members of the ICC were: Adobe Systems Incorporated, Agfa-Gevaert N.V., Apple Computer, Inc., Eastman Kodak Company, FOGRA-Institute, Microsoft Corporation, Silicon Graphics Inc., Sun Microsystems, Inc., and Taligent, Inc. Today there are now approximately seventy members across the photographic and printing industry. There are also six honorary members, including Rochester Institute of Technology, home to the Munsell Color Science Laboratory.

For color management to be successful these industry giants realized that there was a need for all devices

[1] www.color.org

and software created by different companies to be able to communicate with each other. To accomplish this, they combined to develop the framework for a color management system that utilized ICC profiles developed to a standard format. The current version of the standard is Specification ICC.1:2004:10 and can be found at www.color.org.

Chromaticity Diagram and Chromaticity Values

Before going further, we need to explain a few of the tools needed to understand CM. Most tools used to examine the contents of an ICC profile will use a *chromaticity diagram* to display a color gamut. See Figure 10-3. The chromaticity diagram was developed by the CIE (International Commission on Illumination). In 1931, the CIE defined a color space referred to as CIE XYZ. The XYZ values are called *tristimulus values* and represent three imaginary primaries. These values are determined by integrating the spectral power distribution of the light source, the spectral response of the sample, and the spectral response of the human visual system. See Appendix D. The difficulty when working with tristimulus values is that they cannot be visualized, meaning if you are provided with an X, Y, and Z tristimulus value and asked what color it represents, it would be a very difficult if not impossible task for most to accomplish.

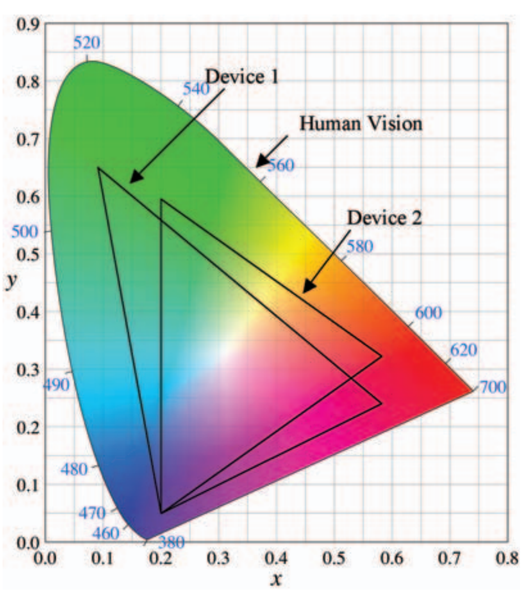


Figure 10-3 Chromaticity diagram.

Realizing this, the CIE has also defined a method to transform tristimulus values into *chromaticity coordinates* that can be plotted on a chromaticity diagram. These values are xyY. The Y is a luminance value and is not plotted. The chromaticity coordinates x and y are calculated according to Equations 10-1 and 10-2 below.

$$x = \frac{X}{X + Y + Z} \qquad \text{(Eq. 10-1)}$$

$$y = \frac{Y}{X + Y + Z} \qquad \text{(Eq. 10-2)}$$

These chromaticity coordinates allow hue and saturation to be plotted on a chromaticity diagram independent of luminance (see Figure 10-3). Pure colors plot along the outside of the horseshoe shaped diagram referred to as the spectral or monochromatic locus. The numbers in blue indicate the wavelength of light in nanometers. The chromaticity diagram is used in color management to illustrate color gamuts and white points.

Color Gamut

A color gamut is the set of colors that a device can produce.

A *color gamut* can be defined as the set of colors that a device can reproduce. Human vision has the largest color gamut. Unfortunately there is not a device available that can reproduce every color that we can see. Color gamuts are usually represented on the chromaticity diagram as shown in

Figure 10-3. The chromaticity coordinates of the pure red, green, and blue are calculated and plotted. Lines are drawn connecting the three points. Any color that falls in the interior of the triangle can be reproduced; any color that is outside the triangle cannot be reproduced and is referred to as an *out-of-gamut color*.

An out-of-gamut color cannot be accurately reproduced and must be remapped to an in-gamut color.

This is one of the problems that has to be addressed by color management. For example, when the color gamut of the monitor is larger than the color gamut of the printer, how are the out-of-gamut colors going to be printed? This is handled by use of *rendering intents* in CM.

Rendering Intents

The ICC specifies four different rendering intents; perceptual, saturation, relative colorimetric, and absolute colorimetric. These will be discussed later. Rendering intents are the methods the CM software engine uses to handle out-of-gamut colors. Referring to Figure 10-3, out-of-gamut colors would be those colors that exist in the Device 1 color gamut but not in the Device 2 color gamut.

There are two basic methods for handling out-of-gamut colors. The first is *gamut clipping*. In this method, every out-of-gamut color is mapped to the closest color that is in gamut. See Figure 10-4. In this case, several different input colors can be mapped to the same output color. This can cause a loss of tonal variation in highly color-saturated areas.

The second method is *gamut compression*. In this method, the larger input gamut is compressed to fit inside of the smaller output color gamut. However, to accomplish this, the smaller gamut is first compressed to make room for the larger gamut.

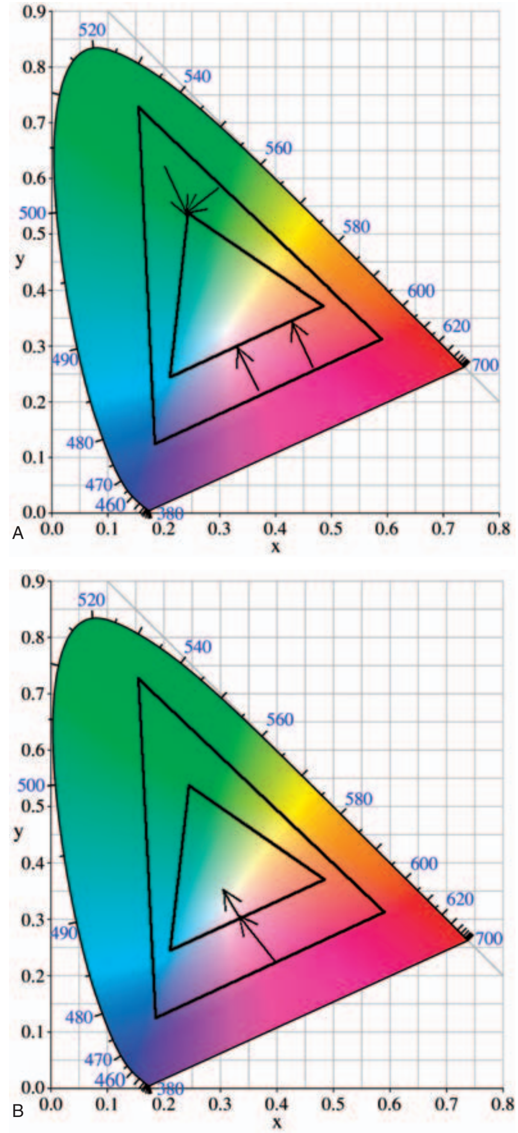


Figure 10-4 Illustration of (A) gamut clipping and (B) gamut compression.

In this method, some colors that were perfectly reproduced prior to the compression will be changed after compression. This can also lead to loss of some tonal variation in highly color-saturated areas.

Rendering Intents

As mentioned earlier, there are four rendering intents: *perceptual*, *saturation*, *relative colorimetric,* and *absolute colorimetric*. Each has its own specific characteristics and applications.

The *perceptual rendering* intent is mainly used for pictorial images. This rendering intent tries to preserve luminance or brightness over saturation and hue information. This is done because an observer is more likely to notice changes in brightness over subtle changes in hue. The perceptual rendering intent is the only one that uses gamut compression to handle gamut mapping; the remaining three use gamut clipping.

The *saturation rending* intents primary use is with graphics, such as company logos or pie charts. With these types of images, it is believed that bright colors that grab the attention are best. The saturation rendering intent will put emphasis on mapping out-of-gamut colors to a nearby color that is highly saturated. This may result in a color shift from the original image to the reproduction. However, human color memory is poor. We will often remember the sunset on a beach as being much more colorful that it was. Keeping this in mind, there are times when the saturation intent, which favors brilliant colors, will produce very pleasing color photographic images.

The *absolute rendering intent* is used when strict color conversions are necessary and is usually used when you want to proof what the final product will look like. For example, an image needs to be proofed for reproduction in a magazine. The printer we have to work with is a photographic-quality printer that uses a bright white paper. The paper used in the magazine is of lesser quality and has a white point that is darker than the photographic paper. The absolute-rendering intent can be used to map the white of the photographic paper to the white of the magazine paper. All the remaining colors are then mapped accordingly. This allows for proofing of the final product to be done without having to print it on the magazine paper.

The last rendering intent is *relative colorimetric*. In this intent, the white point of the source is mapped to the white point of the destination. This is referred to as *white point compensation*. All the remaining colors are shifted accordingly. The resulting image may be slightly brighter or darker than the original, but the whites will match. This intent will also often work well with photographs.

Calibration vs. Characterization

The terms *calibration* and *characterization* are often used interchangeably in photography and CM. They do not mean the same thing.

Calibration is a process of returning a device to a known standard. For example, if you have a scale that is no longer reading 0 pounds when there is nothing on it, the scale can be adjusted back to zero or calibrated. In the world of digital photography, if a printer, monitor, or scanner can be adjusted back to a known standard, then it can be calibrated.

The four rendering intents in CM are perceptual, saturation, absolute, and colorimetric.

Characterization is the process of determining how a device is performing. This would include what its capabilities and limitations are. As an example, we can characterize the performance of a camera. This can be done by testing the camera for a linear response, determining its spectral response, determining the noise level present, and determining the range of illuminances it can record. Characterization describes the behavior of the device. These characteristics are used to set the standard for calibration. When something in a device's characteristics change a new standard for calibration may have to be developed. The

need to re-characterize a device usually becomes apparent when the device can no longer be calibrated, which often indicates its characteristics have changed.

All the parts of a digital system—the camera, monitor, scanner, printer, and any hardware used in the CM process—are described in mathematical terms that a computer can then use. This allows us to characterize all of these devices. The term used for this characterization is a profile or more specially an *ICC profile*.

Color Spaces

There are two types of color spaces: device-dependent and device-independent color spaces. A device-dependent color space is tied to the behavior of a specific device such as a camera or monitor. Every device defines its own device-dependent color space. For example, the color space of a monitor is defined by a finite set of RGB values that are used to control the monitor's output, or a CMYK printer's color space depends on the finite combination of the CMYK dyes that can be used to create a print.

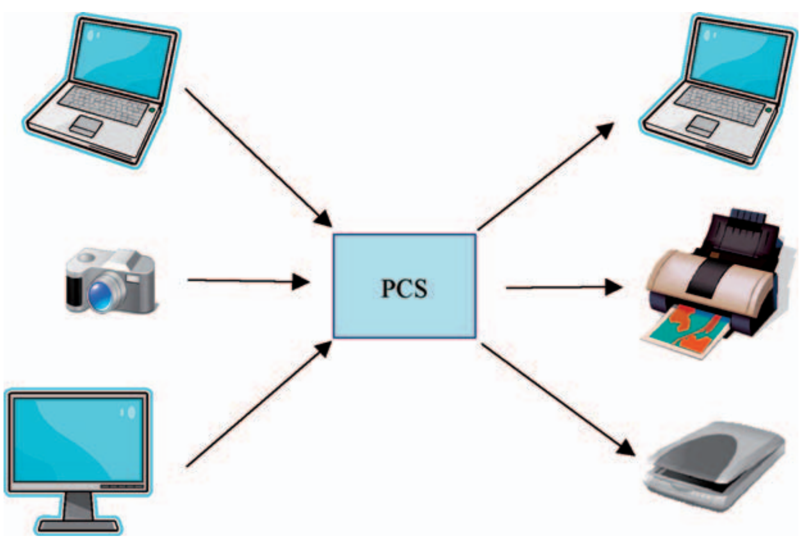


Figure 10-5 A graphical representation of color management.

A device-independent color space, on the other hand, uses numerical values to model human vision. There are many such color spaces, but in CM there are two that are used—the CIE XYZ space and the CIE LAB space discussed in Chapter 9. These two color spaces are used in CM and the profile connection space.

What Is an ICC Profile?

An ICC profile is used to describe or define the relationship between a device-dependent color space, such at the RGB values of a monitor to the corresponding values in a device-independent color space such as CIELAB. Profiles follow the standard cross-platform format defined by the ICC so that they can be used with any software or hardware that follows the standard.

Profiles can be device-specific such that they describe a single device, such as a camera or scanner. Profiles can also be abstract so that they describe a color space such as CIELAB.

Profile Connection Space

Bringing all this information together is the *profile connection space* or PCS. The PCS takes Figure 10-2 and simplifies the process as shown in Figure 10-5. Now the user no longer has to define the relationship between all possible devices. Instead, a profile is developed that defines the relationship between a device and the PCS. For example, a camera profile would define the relationship between the RGB digital counts in the camera to the PCS, or a printer profile would define the relationship between the PCS and the CMYK values required for the printer. Both of these are one-way profiles. There are profiles such as a monitor profile that define both

the relationship from RGB pixel values to the PCS and also the reverse. Therefore, by defining the relationship between a device and the PCS any two devices can now easily communicate through the use of ICC profiles.

Profile Classes

There are several classes of profiles designed for specific reasons.

- *Input profiles* describe scanners and digital cameras. This type of profile is a one-way profile. It can only take input and convert it to PSC space. You cannot output data to a scanner or camera so there is no need for these profiles to provide a two-way path.
- *Display profiles* describe monitors and display devices. A display profile is a two-way profile because a display device can act as both an input device and an output device. You can create an image on your monitor and want to reproduce it on your printer. Here the monitor is acting as an input device. On the other hand, if you display an image from a camera onto a monitor, it is now acting as an output device. For example, a two-way profile can take an image from a monitor and move it to the PCS or it can take an image in the PCS and display it to the monitor.
- *Output profiles* describe printers and presses. An output profile is also a one-way profile because it only needs to take an image from the PCS and send it to the output device.

Building a Profile

Many devices, such as cameras and printers, come with profiles provided by the manufacturer often referred to as "canned profiles". These profiles have been created for the "average" device. For example, the profile that comes with an inkjet printer is the profile that was developed based the average performance for that printer. In many cases, this will work fine, however there are times when it may be necessary to create a unique profile for that printer. For example, a canned profile for an Epson printer will have been developed using Epson inks in the printer. If you use inks made by another manufacturer the canned profile may no longer produce satisfactory results. There are many products available to accomplish this that range in price from the very affordable to the very expensive.

All of these products come with software that steps the user through creating an ICC profile. The user will be prompted to set the necessary parameters for the creation of the profile, such as the device type with options including a scanner, printer, camera, or projector among others. The type of target being used, such as the IT8 target shown in Figure 10-6, must be designated. These are available in reflection and transmission versions. A reference file is always provided with these targets, which provides the software with the color information it is trying to match. If the profile is for a display device such as an LCD or

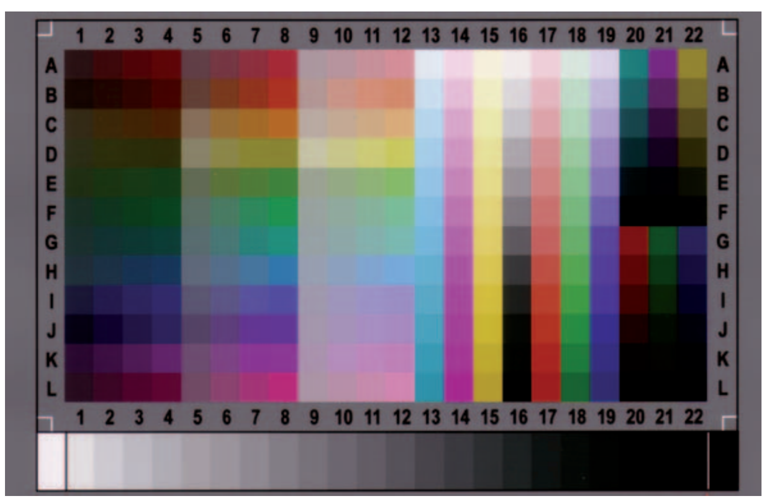


Figure 10-6 IT8 target used for ICC profile creation.

projector, the desired white point and gamma must also be selected.

When all the set-up parameters have been determined, the color patches that are printed or displayed must be measured. This is usually done with a colorimeter or a spectroradiometer. The data is then provided to the software, which then creates the profile.

Using an ICC profile

ICC profiles are applied in several manners. Many cameras will embed the camera default profile in the output image file. This can be removed using image editing software if necessary. Most ICC profiles are applied within image editing software while preparing the image for printing.

Review Questions

1. Who developed and governs the standard for ICC profiles?
   A. American National Standards Institute
   B. International Commission on Illumination
   C. International Color Consortium
2. What is the goal of color management?
   A. to make all devices have the same color gamut
   B. to assist in achieving the same appearance of an image on all devices
   C. to have all devices use the same ICC profile
3. In most color management software, color gamut's are displayed on a
   A. chromaticity diagram
   B. on a CIELAB plot
   C. on a polar coordinate plot
4. Chromaticity coordinates are calculated from
   A. CIELAB values
   B. RGB pixel values
   C. tristimulus values
   D. CMYK values
5. A color that falls outside of a devices color gamut is referred to as
   A. an out-of-gamut color
   B. as a dark color
   C. as color with high saturation
6. How many rendering intents are used in color management?
   A. 2
   B. 3
   C. 4
   D. 5
7. Which rendering intent using gamut-compression to handle out-of-gamut colors?
   A. perceptual rendering intent
   B. saturation rendering intent
   C. absolute rendering intent
   D. relative colorimetric rendering intent
8. A digital camera would require what type of profile?
   A. input profile
   B. display profile
   C. output profile

chapter

11

Color Reproduction

Photograph by David Kelbe, Imaging Science student, Rochester Institute of Technology.

Objectives of Color Reproduction

When considering the properties required of color photographic materials, it is necessary to include the purpose for making the photograph. Generally, the objective of color photography is to produce either an accurate color photograph or a pleasing color photograph. Accurate color reproduction implies a certain correspondence of the colors in the photograph to those of an original scene. When the viewer is familiar with objects in the photograph, having the colors in the reproduction match the viewer's memory of those in the original would be preferable. With a much more demanding form of accurate color reproduction, the photograph is held in the hand and critically compared directly to the original scene or object. Except with very simple subject matter, no color photographic systems are capable of fulfilling this definition of accurate color reproduction.

There are at least three major reasons why color photographic systems are unable to achieve accurate color reproduction—they are physical, physiological, and psychological in nature. The most troublesome of the physical reasons is that the dyes employed to construct the photographic image are not the same colorants that existed in the original subject. This will affect the range of colors or color gamut that can be reproduced. Furthermore, the dyes have unwanted absorptions that limit their ability to accurately simulate the real-life colors.

Generally, the objective of color photography is to produce either an accurate color photograph or a pleasing color photograph.

The human visual system adapts its color sensitivity to different visual environments, whereas color films do not.

Among the physiological factors is the fact that the human eye records the original subject colors in a fashion far different from that of a color film. Because the spectral response of color film or digital sensors differs from that of the eye, the various wavelengths of light reflected from the subject will be encoded (analyzed) in a different way. Additionally, because the eye adapts its sensitivity to the current visual field, its spectral response changes frequently.

Finally, it is obvious that a photograph is not an original scene, but rather something derived from it. It is two-dimensional, typically much smaller than the original scene, and viewed under significantly different lighting conditions than the original scene. Thus the perceptual conditions are significantly different when viewing a photograph than when viewing the original scene. In other words, the dyes or inks in the photograph may be physically identical to those in the original subject and present in the same quantities, but still not give an accurate color reproduction because of these psychological differences.

Most often the goal is pleasing color reproduction, which can also be defined in a variety of ways. For example, it is possible to differentiate between acceptable color reproduction and excellent color reproduction. Acceptable color prints can be defined as those containing a reasonable resemblance to the colors in the original scene. The color prints produced by amateur photofinishing labs using automated equipment and the color prints from instant cameras are examples of generally acceptable color photography. Every color photographic process has certain defects and limitations, which may work strongly against a particular subject color. However, for every subject, a most pleasing print can be made by whatever process is used.

To obtain such an excellent print may require the use of special procedures, such as retouching, color masking, or digitally manipulating it with computer digital image processing software. This is the nature of the work performed by professional photographers and custom-color printing laboratories, and these are examples of what is termed excellent color photography. Obviously the differences between acceptable and excellent color reproduction are a matter of opinion, and as such highly depend upon the audience. Thus, the definition of pleasing color reproduction will ultimately be determined by the user.

It is safe to say that if accurate color reproduction were the most important objective in color photography, the wide proliferation of color photographic systems would never have occurred. The majority of photographers require only pleasing color reproduction, which is the principal objective of most color photographic endeavors. Cost and convenience may be as important to users as the quality in selecting a color system.

Additive and Subtractive Color Formation

All color reproduction systems operate on the assumption that the human eye contains three different types of color receptors or cones. Many experiments show that almost all colors can be produced through the appropriate mixture of red, green, and blue light. Although many theories of color vision have been proposed and used to describe various visual phenomena, the trichromatic theory of color vision offers the most satisfactory

explanation of color perception as it relates to color photography. Thus, in order for a color photographic system to be successful, it must be capable of recording and controlling the red, green, and blue components of the light being reflected, transmitted, or emitted by the subject. There are two basic methods for controlling the color of the light produced in a color reproduction system—*additive color mixture*, which involves combining red, green, and blue light, and *subtractive color mixture*, which involves colorants that selectively absorb red, green, and blue light.

In an additive system, it is possible to produce a wide variety of colors by mixing various amounts of red, green, and blue light. This can be illustrated by using three identical projectors, each equipped with a different colored filter (red, green, and blue) and aimed at a projection screen. Equipping each projector with a variable aperture will allow the illuminance of each color to be adjusted to create brighter or darker colors. Overlapping the blue and the green lights and altering the illuminance of each of the lights will produce a series of blue-green or cyan colors.

Adding the red light to the system and overlapping it with the blue light will result in a series or red-blue or magenta colors. Likewise, overlapping the red light with the green light will produce a series of yellow colors.

Figure 11-1 shows the results of such a system. Each of the three beams of light is falling individually on the screen and also overlaps the other beams. That cyan is formed where the blue and green overlap is not surprising, nor is the formation of magenta from the combination of blue and red light. Visually, the colors produced are consistent with the contributions made by the primary colors. However, for the mixture of red light and green light to appear yellow is a somewhat amazing result, since yellow in no way resembles the red light and the green light. This phenomenon is related to the theory of color vision. Where the beams of the three projectors overlap, the color white is produced. The area of the screen where no direct light from any projector falls would appear black. This illustrates the fundamental method of additive color formation.

The word *additive* implies that adding together different amounts of the three colors of light produces different colors. All additive color reproduction systems require the use of the three colors represented in this example: red light, green light, and blue light. Consequently, these colors are referred to as the *additive primaries*. Table 11-1

Figure 11-1 Additive color system.

Table 11-1 Basic facts of additive color formation (the mixing of lights)

Lights	Produce
Blue light plus green light	Cyan
Blue light plus red light	Magenta
Green light plus red light	Yellow
Blue light plus green light plus red light	White
No light	Black

lists the basic facts of additive color formation using these three additive primaries.

By effectively controlling the operation of the three projectors, practically any color can be produced. Thus the attributes of colors—*hue*, *lightness*, and *saturation*—can all be controlled by changing the amounts of red, green, and blue light falling on the screen. About the only colors that can't be produced are *spectral colors*, because they are too saturated to be simulated with this method.

Both additive and subtractive color reproduction systems are based on controlling red, green, and blue light.

There are two additional ways to employ the principles of additive color formation. A single projector can be used to project three colored images in rapid succession with red, green, and blue following each other so rapidly that the eye cannot distinguish the individual projected colors. Thus the mixing of the three lights is achieved through the perceptual phenomenon known as *persistence of vision*. This technique is referred to as *temporal color mixing* and is currently used in DLP systems.

There are various ways by which red, green, and blue light can be combined, including superimposing, spatial blending, and temporal blending.

In an alternative process, small transparent bits of red, green, and blue are placed side by side to form the picture. The bits are so small that the eye cannot readily distinguish them as colored spots. This is the method employed in CRTs used in color television and computer monitors. The picture is composed of small spots of red, green, and blue light from the phosphors coated on the screen. Observed from the proper viewing distance, these spots blend to form the color image, and with their intensities electronically controlled they reproduce the colors of the original subject. This method is referred to as *spatial color mixing* or *partitive mixing*.

Cyan, magenta, and yellow subtractive primary colorants respectively absorb red light, green light, and blue light.

In summary, additive color formation is characterized by the mixing of lights. Since the human color visual system has three different types of color receptors (red, green, and blue), the colors of the three lights used must be red, green, and blue. The additive mixture of lights can be achieved through either temporal fusion or spatial fusion, as well as by physically mixing the lights.

The alternative to additive color formation is *subtractive* color formation. It is characterized by the mixing colorants (dyes, pigments, paints, and inks). Although subtractive synthesis involves a significantly different principle, such a system can produce nearly the same range of colors as the additive system. In order for a subtractive system of color formation to be successful, the colorants must be capable of controlling the red, green, and blue light components of the white viewing light. As a result, only three colorants can meet this requirement: cyan, magenta, and yellow. Cyan is used because it absorbs red light and reflects (or transmits) blue and green light, creating its blue-green appearance. Magenta is used because it absorbs green light and reflects (or transmits) blue light and red light, causing its blue-red appearance. Yellow is used because it absorbs blue light and reflects red and green light. As a result, the subtractive primaries of cyan, magenta, and yellow can be summarized as follows:

cyan = minus red
magenta = minus green
yellow = minus blue

Figure 11-2 illustrates the results of mixing various amounts of the cyan, magenta, and yellow colorants. Initially the paper is illuminated by white light, which contains nearly equal amounts of red, green, and blue light. Since

Figure 11-2 Subtractive color system.

Table 11-2 Basic facts of subtractive color formation (mixing of pigments)

Colorant	Absorbs	Produces
Cyan	Red	Blue-green (cyan)
Magenta	Green	Blue-red (magenta)
Yellow	Blue	Green-red (yellow)
Cyan plus magenta	Red and green	Blue
Cyan plus yellow	Red and blue	Green
Magenta plus yellow	Green and blue	Red
Cyan plus magenta plus yellow	Red, green, and blue	Black
No colorant	Nothing	White

the paper is white, it reflects white light, again consisting of nearly equal amounts of red, green, and blue light. Where the yellow colorant is mixed with the cyan colorant, the area of overlap produces the color green. The yellow colorant absorbs the blue portion of the white light and the cyan colorant absorbs the red portion of the white light, leaving only the green to be reflected back to our eyes. Similarly, where the yellow and magenta colorants overlap, the color red appears. The blue light is absorbed by the yellow colorant and the green light by the magenta colorant, leaving only the red light to be reflected to our eyes. Finally, where the cyan and magenta colorants overlap, the color blue appears. This occurs because of the red light absorption by the cyan colorant and the green light absorption by the magenta, leaving only the blue light component of the original white light to be reflected to our eyes. A wide variety of hues can be reproduced by mixing varying amounts of these three colorants.

Varying the amount of all three primaries in the required proportions will produce a range of neutral hues varying from white to black. Table 11-2 summarizes the results of mixing pigments. The use of the term subtractive color formation for this system is appropriate, because it depends upon the use of substances that remove varying amounts and colors of light from an initially white source of light.

In many subtractive printing systems used today a fourth colorant or ink is used, black. These systems are referred to as CYMK, K representing the black. This occurs for two reasons. In practice it is often difficult to produce a true black using cyan, magenta, and yellow inks. The resulting color is often a muddy brown in appearance. These three colored inks are also expensive. Adding the black ink solves both problems; it provide a true pure black and is much less expensive to produce. Higher end printers will also separate the CMY inks into two separate inks. For example, including a light and dark magenta, cyan, and yellow ink. This provides better color reproduction.

The Recording of Color (Analysis Stage)

All color photographic systems consist of two major stages—*analysis* and *synthesis*. First, the colors of light from the subject must be recorded in terms of

primary colors—typically, red, green, and blue—which is referred to as the analysis stage. Second, to reconstruct the photographic image the process must be able to control the red, green, and blue light that will ultimately reach the viewer of the image—which is referred to as the synthesis stage.

The oldest and most fundamental method of achieving the first stage is to use red, green, and blue filters with black-and-white panchromatic film, which is sensitive to red, green, and blue light. Figure 11-3 illustrates this approach to color analysis. The subject is first photographed through each of the filters on three separate sheets of film. After processing, the negatives, called separation negatives, reveal three separate records of the subject. The red separation negative is dense in the areas where red light was reflected from the subject. Similarly, the green and blue separation negatives are records of the green and blue content of the subject.

Notice that the yellow patch of the subject is recorded as a dense area in both the red and the green separation negatives. This is because a yellow object absorbs only blue light and reflects both red and green light. Therefore, both the red and green negatives record light from the yellow patch and produce a heavy density.

The exact density information recorded in this tricolor analysis is determined by various factors including the color quality of the illumination, the spectral characteristics of the

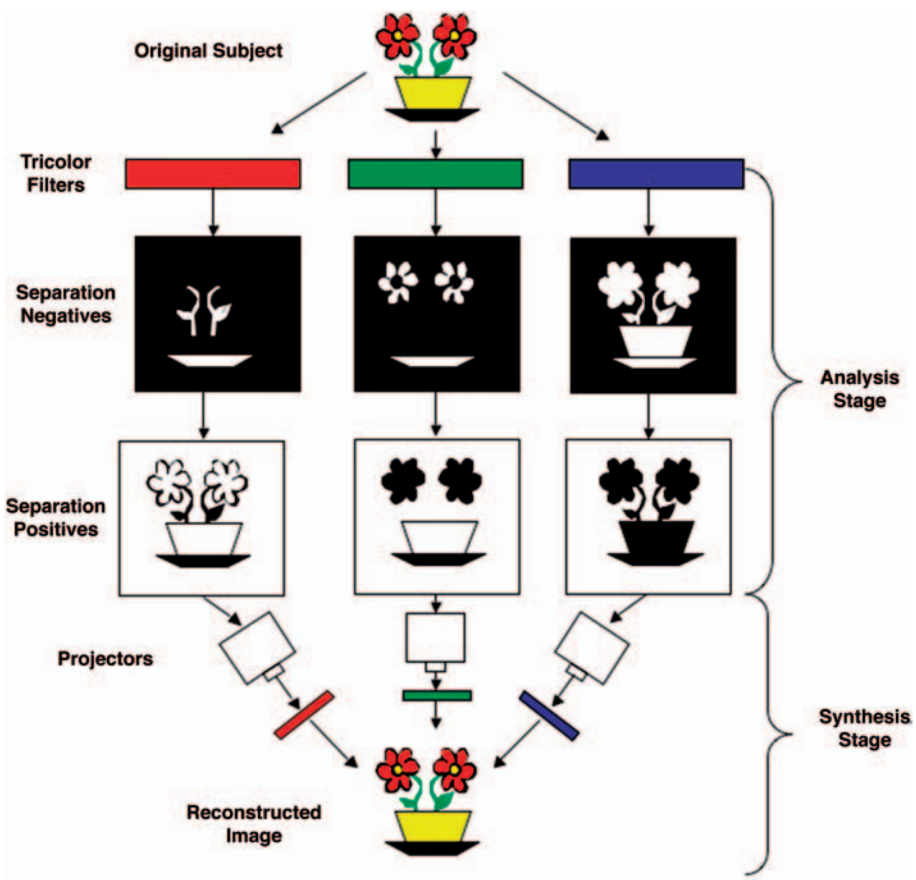


Figure 11-3 The additive system of color photography with both the analysis and synthesis stages illustrated.

subject, the transmission characteristics of the red, green, and blue filters, and the spectral sensitivity of the photographic emulsion. A wide variety of tricolor separation filters and photographic emulsion characteristics have been used for tricolor photography. One combination consists of Eastman Kodak Wratten No. 25 (red), No. 58 (green), and No. 47B (blue) filters with Eastman Kodak T-Max 400 black-and-white film. Figure 11-4 illustrates the spectral density curves for these filters and the spectral sensitivity curve of T-Max 400. Figure 11-4 shows the way in which this combination of filters and film would respond to the red, green, and blue components of the light reflected from the scene.

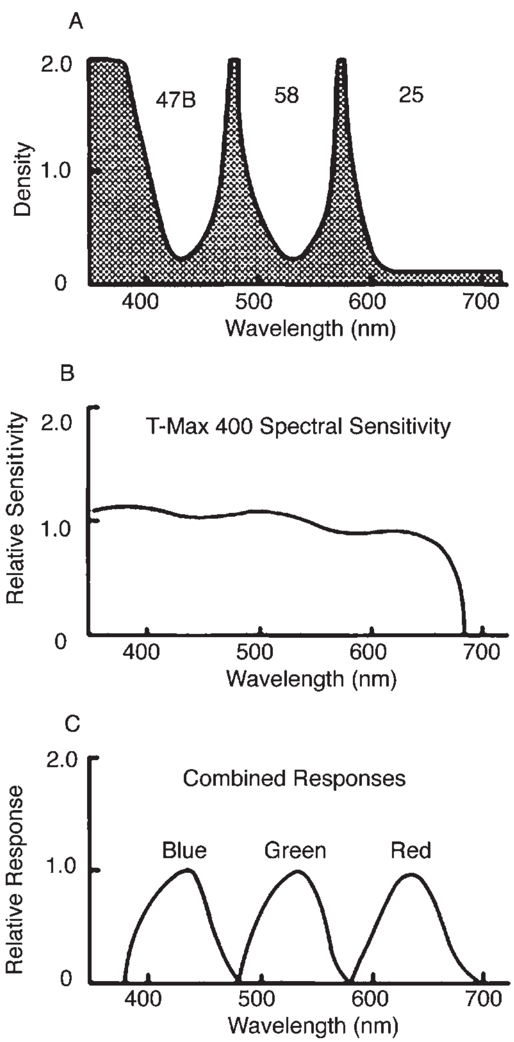


Figure 11-4 Tricolor separations with a black-and-white film. (A) Spectral density curves for tricolor separation filters 47B (blue), 58 (green), and 25 (red). (B) Spectral sensitivity of Eastman Kodak T-Max 400 black-and-white film. (C) Resulting spectral responses when tricolor filters are used with T-Max 400.

The color analysis method used with modern color films is the multilayer approach, whereby three emulsions are coated one above the other on a single base, as illustrated in Figure 11-5. The emulsions are typically separated by interlayers of clear gelatin or colored layers that act as filters. The color analysis is achieved by limiting the emulsion layer sensitivities to the three (red, green, and blue) spectral bands required.

Process red is actually magenta, and process blue is actually cyan.

Analysis and synthesis are involved in all color reproduction processes.

The spectral sensitivities of the multilayer camera speed film are shown in Figure 11-6. On the left are the inherent sensitivities of the blue-, green-, and red-sensitive layers, where it is shown that the green and red recording layers also have blue sensitivity. This problem is minimized through the use of a yellow

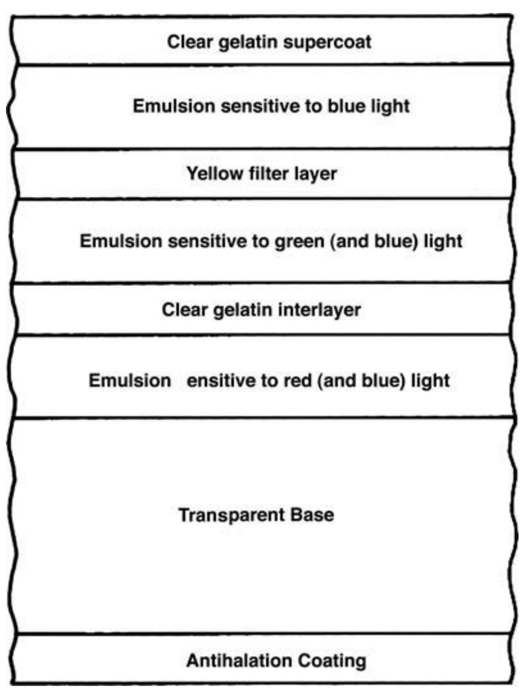


Figure 11-5 Cross section of a typical integral tri-pack color film (not drawn to scale).

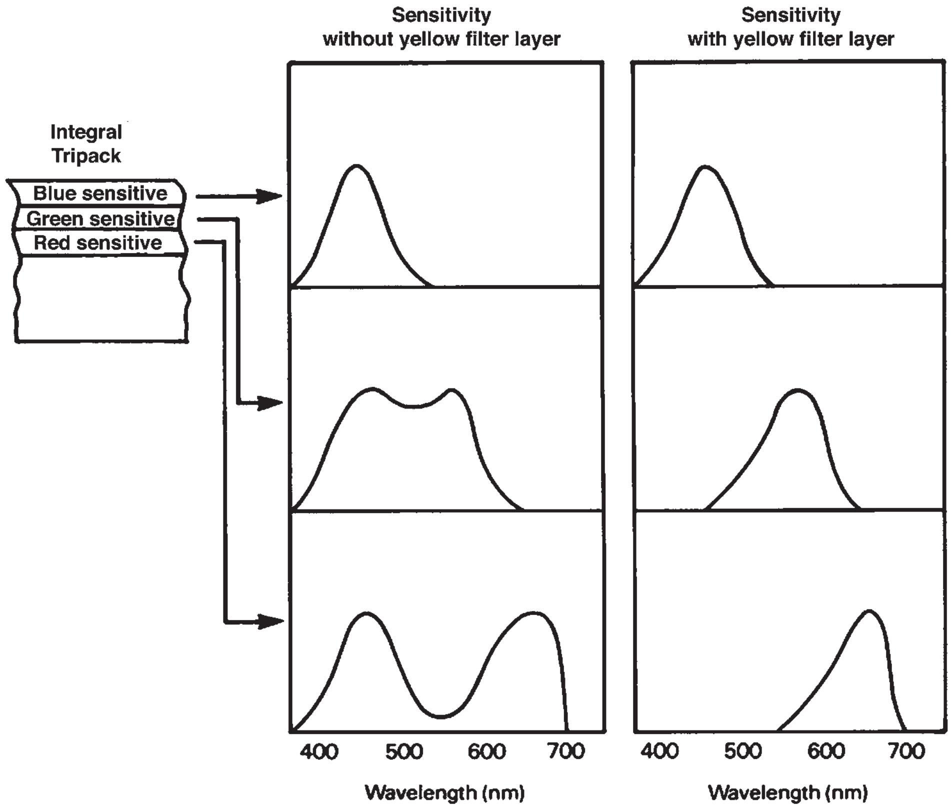


Figure 11-6 Spectral sensitivity of color film with and without the yellow filter layer.

Since all three emulsion layers of conventional color films are sensitive to blue light, a yellow filter must be used to prevent the blue light from reaching the two bottom emulsion layers.

filter layer above the green and red sensitive layers. The top emulsion is sensitive only to blue light, and the green and red light pass through it without effect, allowing the blue light alone to be recorded in that layer. The yellow filter layer immediately below the top emulsion layer absorbs the blue light and prevents it from reaching the two lower (green and red sensitive) emulsion layers. Thus the effective spectral sensitivities of the three layers are, from top to bottom, blue, green, and red, as shown on the left of Figure 11-6.

Consequently, multilayer films possess three more or less independently sensitized emulsions. Such a process requires only a single camera exposure to produce the red, green, and blue record negatives. The three negatives will be stacked on top of each other and, consequently, are inseparable.

At this point, it is important to understand what each of the separation negatives represents. Let us examine the red record negative first. There should only be density present on the negative where there was red light reflected from the subject. There should be no density present on the negative when only blue or green light was reflected. Similarly, the green record negative should only have density where there was green light reflected from the subject and the blue record negatives should only have density where there was blue light reflected from the subject.

In a digital photographic system, it is also necessary to record red, green, and blue “densities” or pixel values separately. Silicon, the light-sensitive material used to create the digital image sensor, responds to all wavelengths of light. One method used to separate the information is to place a

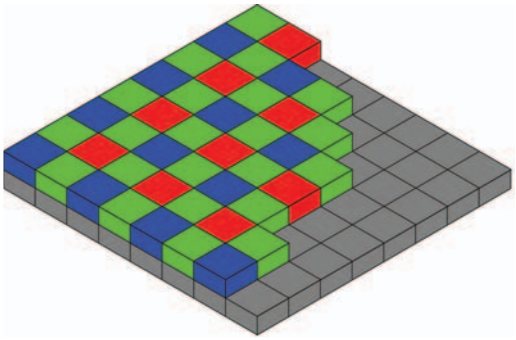


Figure 11-7 Bayer pattern layout.

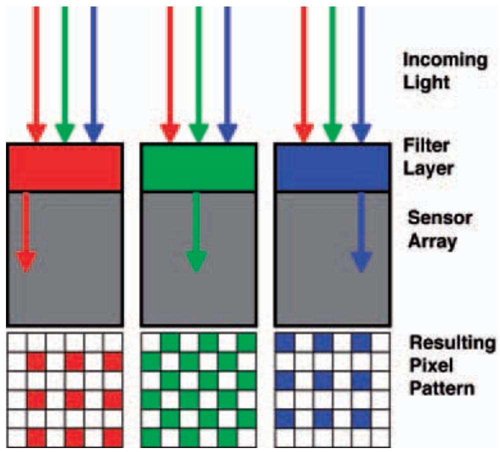


Figure 11-8 Bayer filter array pixel pattern result.

Bayer pattern filter over the sensor. See Figure 11-7. The Bayer filter has alternating red, green, and blue filters in a ratio of 50% green, 25% red, and 25% blue. This ratio was chosen based on the higher sensitivity of human vision to green wavelengths than the red or blue wavelengths. The red filter passes only the red light onto the pixel below, the blue filter passes only the blue light, and the green filter passes only the green light onto the green sensor. See Figure 11-8.

The Bayer pattern filter does not provide a red, green, and blue digital count value for each pixel. The missing digital counts for the intermediate pixels are interpolated to provide a red, green, and blue digital count for each pixel. Interpolation can sometimes result in color fringing along edges.

An alternate sensor configuration is the Foveon X3 sensor, also referred to as a direct image sensor. This CMOS (complementary metal-oxide-semiconductor) sensor stacks three photodiode layers on top of each other. When silicon is exposed to white light, different wavelengths of light will penetrate to different depths. The Foveon sensor takes advantage of this. Blue data comes from the top layer, followed by green then red data layers. This system provides a red, green, and blue digital count for each pixel without the use of interpolation.

The Production of Color (Synthesis Stage)

Once the subject colors have been analyzed and separated into their red, green, and blue components, they must be put back together by some process that recreates the appearance of the original colors. This step is referred to as the color synthesis stage and may be achieved by either the additive or the subtractive methods of color formation previously described.

In all color photographic processes, the viewer is interested in seeing the picture as it originally appeared—as a positive image. In a film-based system, this can be achieved by making three positive silver images, one from each of the three silver separation negatives. Because the densities in the red record negative are formed where red light is reflected from the subject, the densities in the positive will have an inverse relationship with the red content of the scene. The red record positive has the greatest density in those areas where the least red light was reflected from the subject. Similarly, the green and blue record positives will have the greatest density in the

Table 11-3 The relationships between separation negatives and separation positives in terms of density

Subject	Densities of Separation Negatives			Densities of Separation Positives		
	Blue Negative	Green Negative	Red Negative	Blue Positive	Green Positive	Red Positive
Red flower	Low	Low	High	High	High	Low
Green leaves	Low	High	Low	High	Low	High
Yellow pot	Low	High	High	High	Low	Low
Black base	Low	Low	Low	High	High	High
White background	High	High	High	Low	Low	Low

The densities in a red record separation negative indicate where red was present in the original subject.

With reversal color films a red image is obtained by removing blue and green from the white viewing light with yellow and magenta dyes.

areas reflecting the least green and blue light, respectively.

The reconstruction of the subject colors by using these three positives is illustrated in the portion of Figure 11-3 labeled the synthesis stage. Here, three projectors are equipped with red, green, and blue filters. The red record positive is placed in the projector equipped with the red filter. Because the red record positive contains the most density in the areas that reflected the least red light, it will prevent red light from reaching the screen in those same areas. This same positive is thin in the areas that reflected much red light from the subject, and will for those areas permit red light to reach the screen. Therefore, the red light is reaching the screen in approximately the same relative amounts as red light was reflected from the subject.

Similarly, the green and blue record positives are placed in the projectors equipped with the green and blue filters. The three images are projected on the screen so that they are exactly superimposed. When this procedure is carefully performed, a full color reproduction of the original subject will be formed on the screen. Since this color formation is the result of mixing lights, it is defined as an additive color reproduction system.

The relationship between the densities of the separation negatives and the densities of the separation positives is summarized in Table 11-3 for the simple subject matter shown in Figure 11-3. Notice that for the yellow pot the absence of density in the red and green record positives allows red and green light to reach the screen, where they mix together to produce the color yellow. For the black base, no light reaches the screen from any of the projectors. For the white background, all three projectors produce light on the screen, creating the color white.

If the color analysis stage involved a single exposure through a color mosaic screen, the separation negatives will exist side by side in the emulsion. A positive image must be obtained with reversal processing or by producing a negative and contact printing it onto another piece of film. The positive is then placed in register with the original color mosaic screen, and the combination is viewed by transmitted light. Such a system is illustrated in Figure 11-9. Again, the synthesis stage of this process involves a mixture of red, green, and blue light transmitted through the filter mosaic—therefore, it is described as an additive color reproduction system.

The color analysis method that employs a multilayer film as the recording medium contains a set of separation negatives stacked vertically on top of each other. Because the red, green,

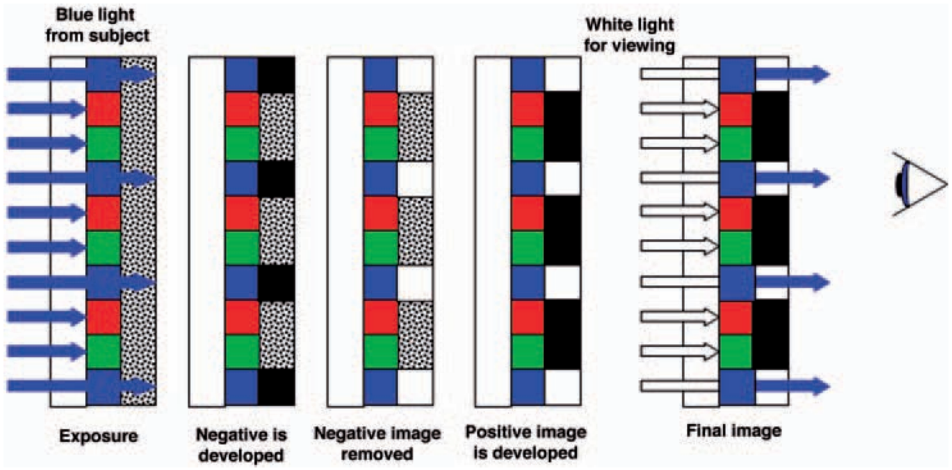


Figure 11-9 Reproduction of color through the use of the mosaic screen process.

and blue records are superimposed and inseparable, it is impossible to employ the active system of mixing red, green, and blue lights to form the color reproduction. Consequently, for multilayer materials an alternative approach to color formation must be used.

In additive color synthesis, silver positives are used to absorb the appropriate amounts of the red, green, and blue light in the three projector system. The alternative approach is to substitute colors (dyes), superimposed in the emulsion, for the three silver positives. In the red record positive, it is necessary to use a dye that absorbs only the red part of the spectrum. A properly formed cyan dye image is nearly as effective in absorbing red light as is the red record silver positive image. The cyan dye will allow the blue light and green light to be transmitted. In the green record positive, it is necessary to use a dye that absorbs only green light. Thus magenta dye is used since it absorbs green light and transmits blue and red light. In the blue record positive, yellow dye absorbs only blue light and allows red light and green light to pass.

Therefore, if the multilayer separation positive consists of cyan, magenta,

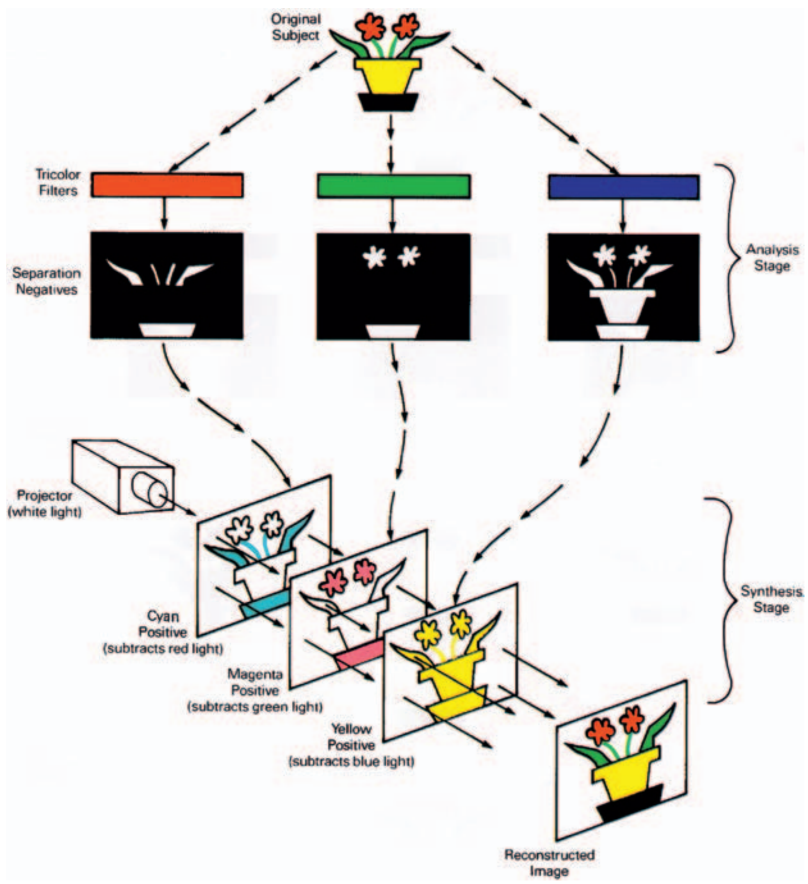


Figure 11-10 Subtractive system of color photography with both the analysis and synthesis stages illustrated.

and yellow dyes, the image can be projected using a single projector. This arrangement is illustrated in Figure 11-10. It is successful because the dye

images, unlike silver, absorb only one color of light, and allow the other two to be transmitted. Therefore, by combining the three dye images in exact registration, a three layer image is produced that requires only one source of light for viewing. The red portion of the white light is controlled by the density of the cyan dye image alone, while the green portion of the white light is being controlled by the magenta dye image alone. The blue portion of the white light is controlled by the yellow dye image. In this fashion, the cyan, magenta, and yellow dye images act as light valves, absorbing appropriate amounts of red, green, and blue light. This system is defined as a subtractive color reproduction process because it involves removing red, green, and blue light from the initial white viewing light.

Table 11-4 summarizes the effects of the three dye positives for the simple subject considered in Figure 11-10. The process affected some of the subject areas in these ways:

1. The *green leaves*. These were recorded only in the green record negative as a heavy density while the other two negatives were thin in the area representing this portion of the subject. When the positives were made, no dye was formed in the magenta positive and a large amount of dye was formed in both the cyan and yellow positive images. In the final reproduction shown in Figure 11-10, the cyan and yellow dyes are superimposed, producing the color green. Because the cyan dye absorbs the red light and the yellow dye absorbs the blue light, the combination absorbs all but the green from the white viewing light.
2. The *yellow flowerpot*. This is recorded as a heavy density in both the red and the green record negatives, but as a thin area in the blue record negative. Since the positives are reversed in density, only the blue record positive will contain any dye. The yellow dye absorbs blue from the white viewing light and this area appears yellow (minus blue).
3. The *black base* of the flower pot. This part of the scene was recorded as a thin area in all three negatives, and as a dense area in all of the positives. This area was, therefore, recorded as a heavy deposit of all three dyes, which when superimposed absorb red, green, and blue light, leaving very little light to reach the viewer.
4. The *white* background. This was recorded as a heavy density in all of the negatives and as a thin area in all of the positives. Since no dye was formed in any of the positives, practically none of the white viewing light is absorbed.

Even with a subject as simple and containing as few colors as this, such a process of subtractive color reproduction can produce a tremendous variety of subject colors. Furthermore, the use of the subtractive process allows for the production of both transmission and reflection color images.

Table 11-4 Analysis of the yellow, magenta, and cyan dye separation positives in terms of the amount of dye formed

Subject	Yellow Positive	Magenta Positive	Cyan Positive
Red flower	Large	Large	No
Green leaves	Large	No	Large
Yellow pot	Large	No	No
Black base	Large	Large	Large
White background	No	No	No

Printing images from digital files works essentially the same way, as a subtractive system. The build up of the cyan, magenta, and yellow dyes happens differently though. An ink-jet printing system places extremely small droplets of ink onto paper to create an image. The amount of ink is determined by the digital count values of the pixels in the image.

Spectral Sensitivity

For a color photographic system to reproduce colors approximately as the eye perceives them, the responses to red, green, and blue light must bear the same relationship to each other as do the responses of the eye to these colors. For example, if a reversal color film has relatively too much sensitivity to blue light, blue objects in the scene will appear too light in the color reproduction, assuming the exposure is correct for the green and the red objects and white objects will appear bluish.

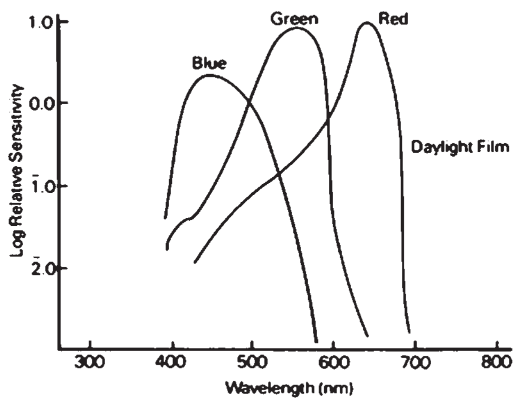
Thus one of the requirements for accurate color reproduction is that the red, green, and blue sensitivity of the initial color recording (analysis stage) must match those of the human eye.

Matching the color sensitivity of the three-receptor systems involved in human vision is a very complex task since the human visual system is constantly changing in its response to light. The perceptual phenomena of color adaptation and color constancy are impossible to duplicate with a color film. The human color visual system can adapt to many different forms of color balance while a color film or digital sensor is limited in its response to a single adaptation level and therefore has a given color balance that is determined at the time of manufacture. In the negative/positive process, it is relatively easy to adjust the color balance during the printing operation. In a digital system, the color balance can be adjusted during image capture or with image editing software later. However, reversal color films provide less opportunity for change, because the image exposed in the camera will determine the positive image on the processed film.

A color film can record the light reflected from the subject with only one particular set of sensitivities. The optimum reproduction of color in a reversal film can be obtained only when the illumination is of the particular color quality for which the film is balanced. As a result, film manufacturers market multilayer camera films of three different spectral responses. Daylight-type color films are designed to be exposed to light with a color temperature of 5500 K, which is the mixture of sunlight and skylight most commonly encountered outdoors. Type A films are designed to be used with light sources operating at 3400 K, which is produced by special photoflood lamps. Type B films are balanced for light sources operating at 3200 K, which is the most commonly encountered type of tungsten lamp in photographic studios.

The difference between color films balanced for 5500 K (daylight) and 3200 K (tungsten lamps) is most easily seen by inspecting the spectral sensitivity curves of the films in Figure 11-11. Such curves indicate the relative sensitivity to light, wavelength by wavelength, for each of the film's three layers. The principal difference between the responses of the two films is in the red sensitive (cyan dye forming) layer, where the response is much lower in the tungsten film than in the daylight film. This is because tungsten sources produce relatively large amounts of red light compared to

Daylight type color films have lower blue sensitivity and higher red sensitivity than tungsten-type color films.



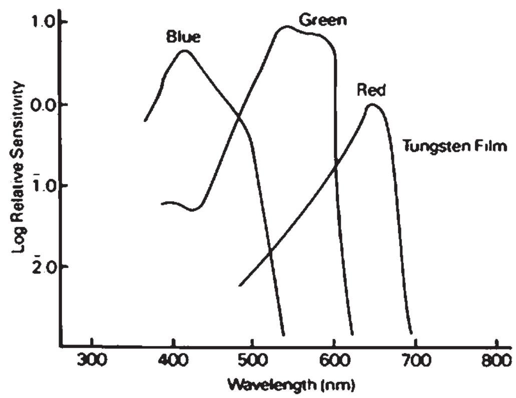


Figure 11-11 Spectral sensitivity curves for daylight-balanced and tungsten—balanced reversal color films of the same speed without the yellow filter that is beneath the blue-sensitive emulsion. This filter prevents blue light from reaching the blue- and green-sensitive and the blue- and red-sensitive emulsions.

blue light, whereas daylight has more nearly equal amounts of blue light and red light. Thus the low red sensitivity of the tungsten-balanced film compensates for this high proportion of red light in tungsten sources, producing a correctly balanced color image.

Cyan dyes absorb considerable blue light and green light even though they should transmit both colors freely.

The blue sensitivity of the green (magenta forming) layer and the red (cyan forming) layer of both films is essentially eliminated by the yellow filter interlayer that is coated between the top blue-sensitive layer and the bottom two layers in the multilayer films. If the tungsten-balanced film is used with daylight illumination without filtration, the resulting transparencies will show a strong bluish cast. Similarly, if the daylight-balanced film is used with a tungsten source without filtration, the resulting color transparencies will have a reddish cast to them. Therefore, when the color film is to be exposed to light of a color quality other than that for which it was balanced, a conversion filter must be used. Even when appropriate conversion filters are used over the camera lens, errors in the rendering of the colors of certain objects may result, and only a practical test of the film, filters, and light source will determine if the results are suitable. Also, notice that there are no color films balanced for fluorescent lighting. Consequently, all color films invariably require color compensating (CC) filters for fluorescent lights. Proper filter use depends upon the film's original color balance and the type of fluorescent lamp used. Recommended filtration for various combinations of color films and fluorescent lamps can be obtained from film manufacturers.

Color balance issues are easier dealt with in digital photography. Digital cameras have many preset color balances such as daylight, tungsten, or fluorescent. Some offer options for sunny daylight or cloudy daylight. These options provide the same correction as color compensation filters do for film-based systems. Upper-end digital SLR cameras often offer a custom white balance setting that allows the photographer to set the white point balance. The photographer points the camera at an object in the scene that should reproduce as white in the final image and sets the white balance to this, essentially creating custom filtration. The last option available is to capture the image in digital raw format and correct for color balance with image editing software prior to display or printing.

Dye Characteristics

As discussed previously, subtractive color formation involves the mixture of the three dyes—cyan, magenta, and yellow. The purpose of the dyes is to control the amount of red, green, and blue light that will be reflected (or transmitted) to the viewer. Therefore, each of the dyes should absorb only one color of light—the yellow dye should only absorb blue light, the magenta dye should only absorb green light, and the cyan dye should only absorb red light. In other words, each dye should only absorb its complementary color and allow the other two primary colors of light to be transmitted freely. However, even the best available dyes, pigments, and printing inks absorb some colors of light that they should transmit—(1) yellow dye absorbs a small amount of green light, (2) magenta dye absorbs a considerable amount of blue light and a smaller amount of red light, and (3) cyan dye absorbs significant amounts of green light and blue light. The easiest way to define the dye properties is to examine the spectral dye density curves of a typical set of cyan, magenta, and yellow dyes. Such a graph illustrates the wavelength-by-wavelength density of each dye. In Figure 11-12, graph A illustrates the spectral dye-density curves for a theoretically perfect set of dyes. The graph shows that each dye should absorb only one-third of the spectrum and allow the other two-thirds to be transmitted, providing for independent control for each of the red, green, and blue light regions.

Graph B shows the spectral dye density curves for a typical set of cyan, magenta, and yellow dyes. The yellow dye shows a high density to blue light (its primary or "wanted" absorption), a small amount of unwanted absorption in the green region, and practically no absorption in the red region. The magenta dye shows a high density in the green region (its primary absorption) and a significant amount of unwanted absorption in the blue and red regions. The cyan dye shows a high density to red light (its primary absorption) and a significant amount of unwanted absorption in the green and blue regions. Based upon the amount of unwanted absorptions, it appears that the yellow dye is the purest and the cyan dye is the least pure.

In order to understand the effects of these unwanted absorptions, consider the problems of attempting to form a neutral (gray) color. Assume that an initial deposit of cyan dye,

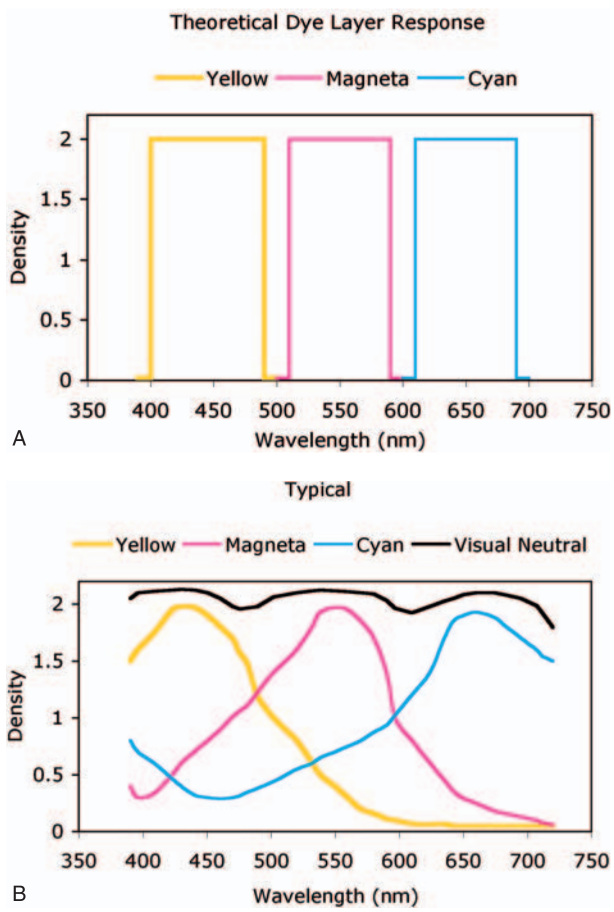


Figure 11-12 (A) Theoretical and (B)typical spectral dye response curves.

Neutral gray areas in color transparencies do not transmit equal amounts of all wavelengths of the white viewing light.

The density obtained with a blue filter densitometer reading of a neutral area on a color transparency is identified as an integral density since it represents the combined densities of all three dye layers with blue light.

which has a primary absorption of red light, is produced. Because the cyan dye has unwanted green light absorption, a lesser amount of magenta dye is required than would otherwise have been used. The magenta dye has significant unwanted blue light absorption, requiring that a lesser amount of yellow dye be formed than would otherwise have been necessary. Therefore, the neutral is formed from unequal amounts of the three dyes because of their unwanted absorptions. Although it is possible to produce a visual neutral in this fashion, the reduction in the magenta and yellow dyes of the process will influence the rendering of other colors such as red, since it is formed from magenta and yellow dyes—green, which is formed by mixing yellow and cyan dyes, and blue, which is formed by mixing cyan and magenta dyes. In other words, these colors and others will be reproduced inaccurately.

This illustrates the fact that the nature of the dyes makes it impossible to obtain accurate reproduction of all colors. Fortunately, accuracy in color reproduction is seldom required. Pleasing color reproduction is the most obvious goal. Color films are invariably designed so that the dyes produce the most pleasing color renditions of such important subjects as skin, grass, the sky, and others familiar to memory. Because color processes are adjusted to produce pleasing reproductions of these memory colors, it is not surprising that slight departures from neutrality occur in the rendering of grays.

This compromise in color reproduction, which is the result of unwanted dye absorptions, does not seriously degrade the quality of a color print or transparency that is to be viewed directly. However, if the color print or transparency is to be duplicated again with the photographic process, the errors in the original are compounded by the errors due to the colorants used in the duplicate reproduction. Consequently, as the chain of color photographic stages gets longer (a duplicate from a duplicate from a duplicate, etc.), undesirable changes in color rendering as well as contrast increase in magnitude.

Color Densities

The measurement of density for colored photographic materials is complicated by the nature of the dye images formed. The spectral dye density curves for the three dyes of a typical color process, together with the curve representing the visually neutral image formed when these dyes are superimposed, are shown in Figure 11-12B. As noted previously, each dye has appreciable density to all wavelengths of light. Therefore, every measurement of the density of a color image (either negative or positive) is simultaneously affected by all three dyes. Furthermore, the visual neutral represented by the top curve, which is produced by mixing these three dyes, departs from a "perfect" neutral, which would yield a horizontal straight line. Since the combined densities of the three dyes are not constant at all wavelengths, density measurements of color images will be greatly influenced by the color characteristics of the light source as well as the color response of the receptor in the densitometer.

Problems arising from light scattering in color materials are much less serious in color materials because the structure of the dye clouds that comprise the color image is much finer than the grains of silver that comprise the image in a black-and-white material. Consequently, the differences between *specular* and *diffuse* densities

for dye images are quite small, with the Q factor approaching 1.0.

Color films consist of three dye layers, each with different spectral characteristics. Since it is possible to generate either one, two, or all three of the dyes in a color image, it is necessary to distinguish between such images. If a color image has all three dyes present, it is referred to as an integral image. If a color image contains only one of the three dyes, it is referred to as an analytical image. The differences in the nature of these images are the source of the following two fundamental classifications of color densities:

1. *Integral densities*. Integral densities are measures of the combined effect of the three superimposed dye layers. No information about the individual contributions of the dyes can be obtained because each dye has significant absorptions to all wavelengths of light.
2. *Analytical densities*. Analytical densities are measures of the individual contributions of the dye layers to the total image and indicate the composition of the image in terms of the amounts of the dyes present.

In practice, integral densities are far more useful because they describe the performance of the image. Therefore, integral density measurements are usually satisfactory for the consumers of photographic materials. Integral densities are usually insufficient for the manufacturer of color materials because they give no direct information about the image composition. During their manufacture, color emulsions are made and coated separately, and thus the manufacturer must have insight into the nature of each layer. Analytical images can be obtained by exposing and processing individual coatings of each layer. An alternative method is to expose a multilayer emulsion through a very saturated narrowband filter, thereby producing dye in only one layer.

If all three dyes are present in the image, it is defined as an *integral image*, and any density measurement made on it is termed an integral density. Likewise, when only one dye layer is present, it is defined as an *analytical image* and any measurement made on it is termed an analytical density.

Each of these two types of color densities can be classified in terms of the information supplied by the measurements. The following subclassifications are typically used:

1. *Spectral densities*. These measure the wavelength-by-wavelength density of the image, and the results are typically displayed as a graph. If all three dyes are present in the image, the resulting data are termed integral spectral densities, and if only one of the three dye layers is present, the results are termed analytical spectral densities. Referring to Figure 11-12B, the uppermost curve would be termed an integral spectral density plot, and the three curves below would be defined as analytical spectral densities since they relate to each of the three dyes. Such information is fundamental to studies of the dyes used in color photographic materials.
2. *Wideband three-filter densities*. These densities are based on the use of three arbitrarily chosen red, green, and blue filters. The densities are termed wideband since the filters have bandwidths of 30 nm to 60 nm. Thus the data that are derived from a color densitometer describe the red, green, and blue light stopping abilities as dictated by the filters that were used in the instrument.

In addition, the spectral response of the densitometer's photodetector can significantly affect the resulting measured values. Therefore, for the purposes of standardization, the American National Standards Institute has defined the following two conditions for color densitometry:

1. *Status A densitometry*: A set of red, green, and blue response functions for the measurement of color photographic images intended for direct viewing (either transmission or reflection). The standard response functions for status A are illustrated in Figure 11-13. In order to achieve these aim response functions, densitometer manufacturers must select a light source, a filter set, and a photodetector whose combined response will approximate (within 5%) these response functions. This is most commonly achieved through the use of a tungsten lamp operating at 3000 K, an S4 photodetector, and the use of Eastman Kodak Certified AA red, green, and blue filters. The peak responses of these functions correspond fairly closely to the peak densities for each of the three dyes in a typical color-positive material. Furthermore, the response functions are narrow enough to allow fairly high densities (above 2.0) to be measured with good integrity (no cross-talk between the spectral bands). Thus a densitometer equipped with such a set of response functions provides color densities capable of detecting small changes in the densities of the image. It is important to note, however, that such red, green, and blue densities are not a direct indication of the appearance of the colors in the image.
2. *Status M densitometry*: The standard used when reading the densities of color images that are to be printed. The red, green, and blue aim response functions for status M densitometry are illustrated in Figure 11-14. Again, densitometer manufacturers must select a combination of lamp, filter set, and photodetector response that approximates these response functions. The use of a tungsten lamp operating at 3000 K, the S4 photodetector, and Eastman Kodak Certified MM

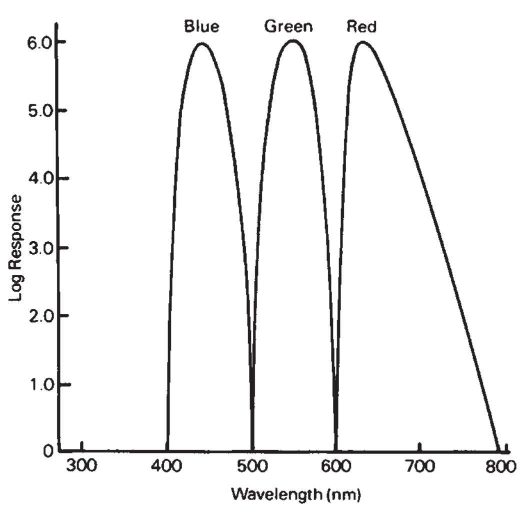


Figure 11-13 Red, green, and blue aim response functions for status A densitometry.

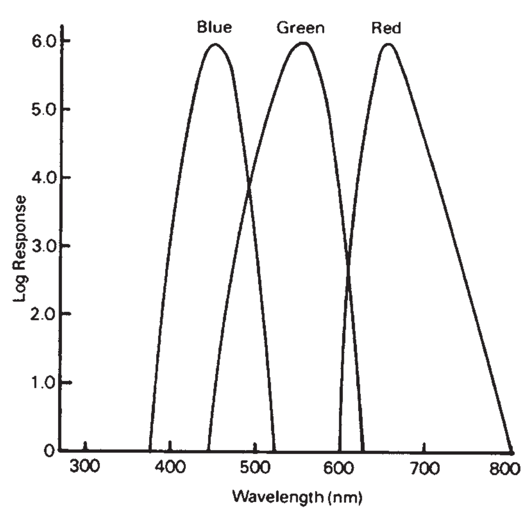


Figure 11-14 Red, green, and blue aim response functions for status M densitometry.

filters meets this requirement; and densitometers so equipped are said to read "Status M Density."

Notice that the response functions for status M show considerable overlap when compared to the status A response functions (that is, they have greater crosstalk). This is intended to simulate the red, green, and blue spectral response functions encountered in color print emulsions. Thus densitometers equipped with these response functions give densities that are descriptive of the printing properties of the image.

The benefit of using densitometers with these standardized response functions is principally a reduction of inter-instrument variability. The result is that densitometers from the same manufacturer and densitometers from different manufacturers tend to show better agreement when measuring the same image. As noted above, if the image being measured consists of all three dyes superimposed, the densities are referred to as integral and if only one of the three dyes is present, such wideband densities are termed analytical. This type of color densitometry is more commonly employed on integral images to obtain information about the performance of the color materials. Further, such readings are often used in conventional process monitoring where it is necessary to determine significant changes in the processing conditions by using standardized control strips.

Regardless of the use of the readings and the filter set actually employed, it is necessary to check the instrument's behavior periodically by using statistical control methods. Periodic readings should be made on standard control patches to detect unwanted changes in the densitometer's response.

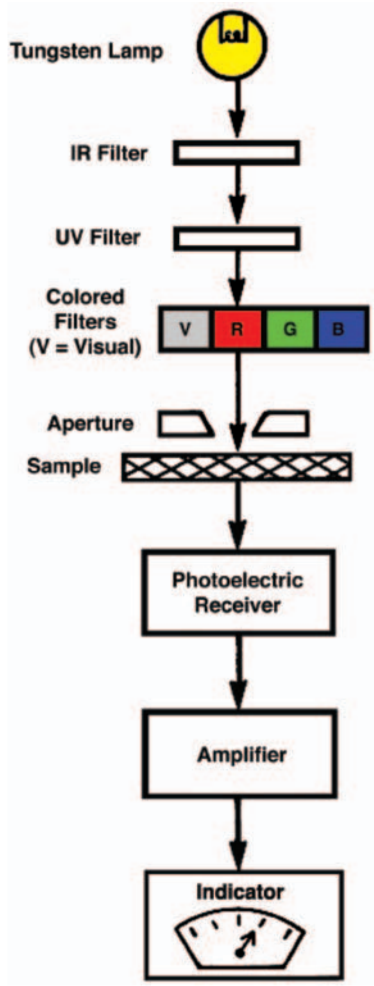


Figure 11-15 Major components of a photoelectric transmission densitometer.

Figure 11-15 is a simplified diagram of the basic components of a transmission color densitometer. The basic parts are (1) a light source that emits light in all regions of the visible spectrum, typically a tungsten lamp operated at 3000 K, (2) a set of wide-band red, green, and blue filters plus a fourth filter that adjusts the instrument response to match that of the eye (visual density), and (3) a photoelectric receiver that senses the light transmitted by the sample being measured. Most commercial color densitometers allow for interchangeable filter sets, so that status A, status M, or non-status three-filter color densitometry can be used.

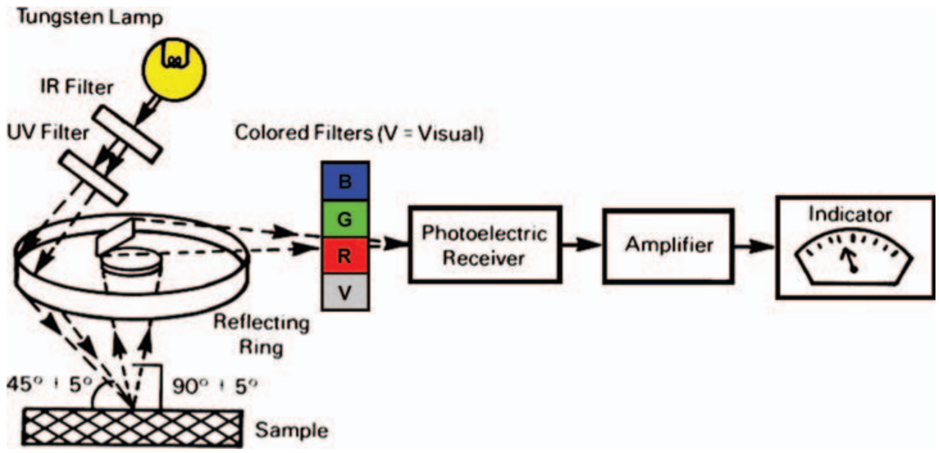


Figure 11-16 Major components of a photoelectric reflection densitometer.

The measurement of reflection color densities requires a significantly different design, as illustrated in Figure 11-16. A tungsten lamp is used to illuminate the sample at an angle of approximately 45°, and the light reflected from the sample is collected over a 5° angle around the perpendicular to the sample. A mirror in the center reflects the light to the receiver after passing through the filter (red, green, or blue) that has been placed in front of the receiver.

Such a design simulates the optimum condition for viewing a reflection image, which is with the illumination striking the image at about a 45° angle with the light that is reflected on the perpendicular being received by the viewer's eye. In practice, however, light reaches the image over a very wide angle as a result of light reflections from the walls, ceilings, floors, etc. Since it is impossible to simulate these conditions in a reflection densitometer, the values that result do not accurately represent most viewing conditions and, as a result, represent an acceptable compromise.

Reflection densitometers can provide useful information about the light-modifying characteristics of reflection photographic images. Additionally, red, green, and blue filters can be used over the receptor to obtain information about the color characteristics of the image.

By far the most commonly used means of determining color densities, integral three filter densities must be interpreted with great care. For example, it is often assumed that a color film will give a good visual neutral if the red, green, and blue densities are equal. In fact, color images with equal red, green, and blue densities usually show a slight color cast. There are at least two reasons for this discrepancy. First, the three dyes that comprise the image each have unwanted absorptions. Second, the overall red, green, and blue response characteristics of the densitometer are considerably different from those of the human eye.

Sensitometry of Color Photographic Materials

The determination of the sensitometric properties of color photographic films and papers essentially involves the same procedures that were discussed in Chapter 5—exposure, processing, image measurement, and data interpretation

through the use of characteristic curves. When exposing the film, the sensitometer must be equipped with a light source that produces the color temperature for which the color film was designed. Any attenuators (neutral density filters and step tablets) must not depart significantly from neutrality, or they will alter the color balance of the light reaching the film.

Figure 11-17 shows the spectral density curves for a variety of neutral attenuators. Notice that the Wratten neutral density filter shows a higher density at the blue end of the spectrum than at the green or red end. Furthermore, photographic silver step tablets also show a slightly higher blue density. When extreme neutrality is required, as when following ANSI standard methods, M-type carbon attenuators are preferred. These attenuators are composed of carbon particles dispersed in gelatin and coated on an acetate base. Additionally, the Inconel-coated materials (iron alloys evaporated onto glass) provide excellent neutrality in the visible region.

It is important to note that all four of these attenuators depart considerably from neutrality in the ultraviolet region of the spectrum. Furthermore, only the Inconel coated material shows good neutrality in the infrared regions of the spectrum. Thus when selecting filters for specialized work involving either ultraviolet or infrared energy, extreme care must be taken in selecting the attenuators.

The exposure time used in the sensitometer must simulate those times that typically will be used with the material in practice. This is to avoid the problem of reciprocity failure. The processing of the sensitometric samples involves either standardized methods (ANSI methods) or techniques used in practice. The manufacturer of the sensitized material is likely the only one to use the standardized methods since this approach would provide information primarily about the emulsion properties. The photographer, however, requires information about the film and its corresponding processing in order to control the quality of the resulting photographic images.

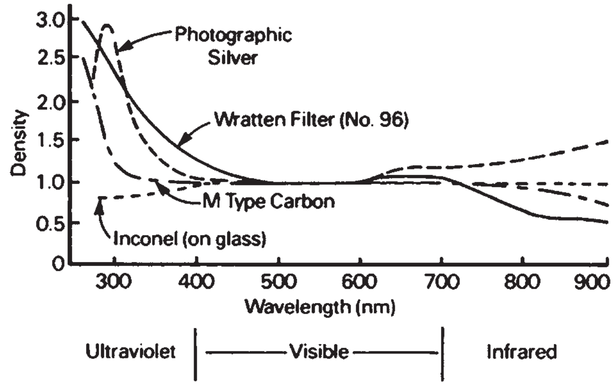


Figure 11-17 Spectral density curves for a variety of neutral attenuators.

Equal red, green, and blue densities in an area of a color photograph do not guarantee that the area will appear neutral.

Gelatin neutral density filters tend to absorb more blue light than green light or red light, and therefore are not entirely neutral.

Reversal color films are capable of producing considerably higher densities than reflection print materials.

In both cases, the resulting color photographic image consists of a set of superimposed cyan, magenta, and yellow dyes. As a result, the image measurement method used typically results in three values—the density to red light (Dr), the density to green light (Dg), and the density to blue light (Db), which are referred to as three-filter integral densities. The problems associated with obtaining and interpreting such data have previously been discussed.

The construction of the characteristic curve for a color film follows the convention discussed in Chapter 5 for black-and-white materials, except that three curves will be plotted for each image instead of one. In cases in which a visual neutral has been formed in the image, it is possible to simply measure the visual density of each step and therefore plot a single curve that is representative of the image. The basic properties of speed and contrast are determined in the evaluation of

the resulting curve. The sensitometric characteristics of a variety of color photographic materials follow.

Reversal Color Films

Examples of *reversal* films include Ektachrome, Kodachrome, Fujichrome, and Agfachrome. The visual density curve for a neutrally exposed and processed reversal color image is shown in Figure 11-18. With a reversal material, increasing amounts of exposure produce decreasing amounts of density in the image. In order to obtain adequate contrast and color saturation in the transparency, the midtone slope is generally between 1.8 and 2.0, which is much higher than for negative materials. Far to the right on the curve is the minimum density, which is the combined result of residual color couplers, stain that was picked up during processing, and the density of the supporting base. The minimum density (visual density) of this area is seldom less than 0.20.

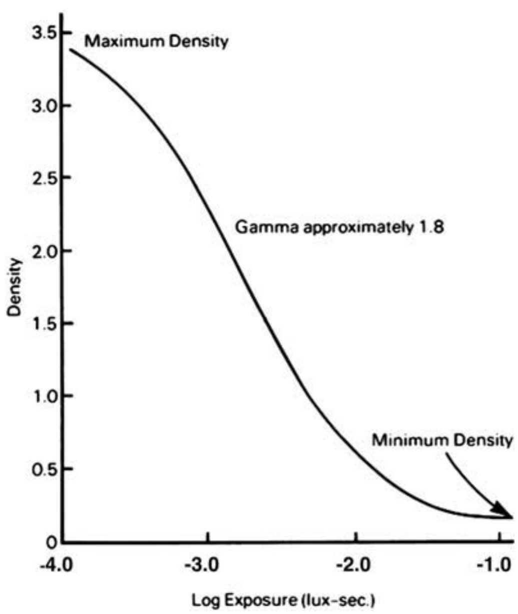


Figure 11-18 Visual density curve from a neutrally exposed and processed reversal color film.

Far to the left of the plot is the shoulder of the curve, where the maximum density, representing no exposure, occurs. For most reversal color films, the maximum density obtainable is at least 3.0, and often greater. Consequently, color transparencies are capable of substantially greater output density ranges (near 3.0) than are reflection print materials. The contrast of reversal films is typically measured as the gamma, with these values usually between 1.80 and 2.0. Additionally, average gradient can be determined between any two points on the curve, and as a result will be different from (lower than) the gamma.

The useful log exposure range of the film is the range of log exposures contained between the minimum and maximum useful densities of the curve. Since the slopes of reversal color films are very steep, they are typically characterized by narrow useful log exposure ranges. Most such films do not exceed a useful log range of 1.90, indicating that an exposure ratio of at best 80:1 can be accommodated. As a result, the amount of exposure latitude (margin for exposure error) is usually quite small.

The speed of a reversal color film is based on the location of two points on the curve that relate to shadow and highlight reproduction, as illustrated in Figure 11-19. Point A relates to highlight reproduction and is located at a density of 0.20 above the minimum density. From this point, a straight line is drawn so that it is tangent to the shoulder of the curve and locates the upper useful point. If this point of tangency falls at a density greater than 2.0, the upper useful point—labeled point B—is simply located at a density of 2.0 above the minimum density. The log exposures are determined for both positions and averaged by adding

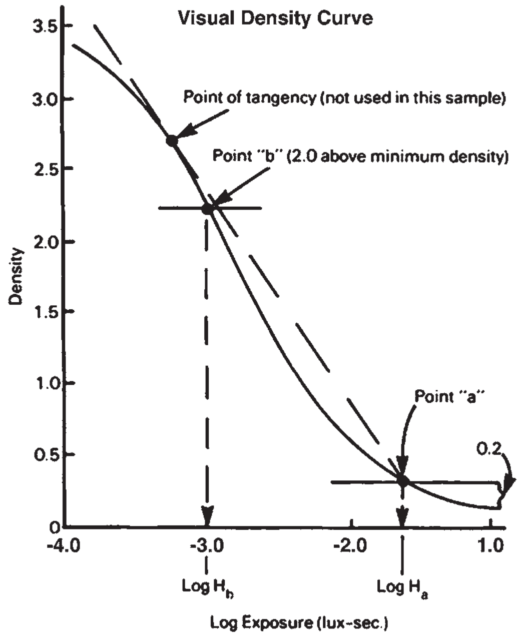


Figure 11-19 Location of the speed points in the ISO (ASA) speed method for reversal color film.

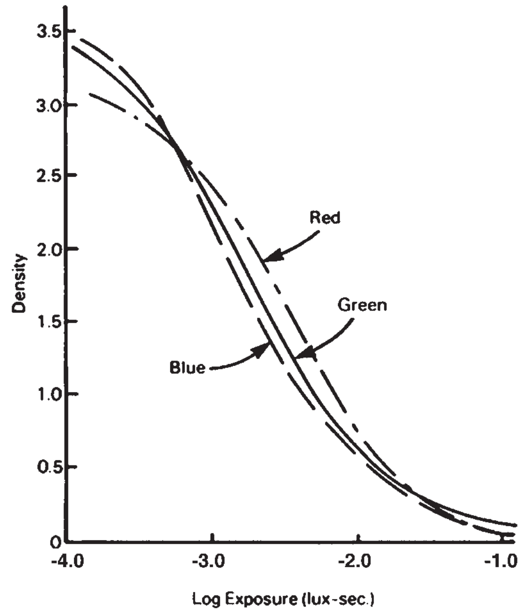


Figure 11-20 Red, green, and blue status A density curves from a neutrally exposed and processed reversal color film. This image is a visual neutral. Because the response of the densitometer is different from that of the human eye, the curves are not superimposed (that is, the image is not a densitometric neutral).

them and then dividing the sum by 2. The resulting value is termed the *minimum log exposure* (log H_m). The antilog is taken and used in the following speed formula (Eq. 11-1):

$$ASA = \frac{I}{H_m} \times 10 \qquad \text{(Eq. 11-1)}$$

Other sensitometric properties of reversal color films can be evaluated by using red, green, and blue density readings and constructing the corresponding curves, as illustrated in Figure 11-20. These curves are the result of reading a visually neutral color film image of a sensitometric strip on a densitometer equipped with the status A response functions. Note that the three curves are not exactly superimposed, indicating that although the image is a visual neutral, it is not a densitometric neutral. Because these curves were derived from a visually neutral strip, they can be used as a reference against which future strips can be compared in order to detect changes in image color.

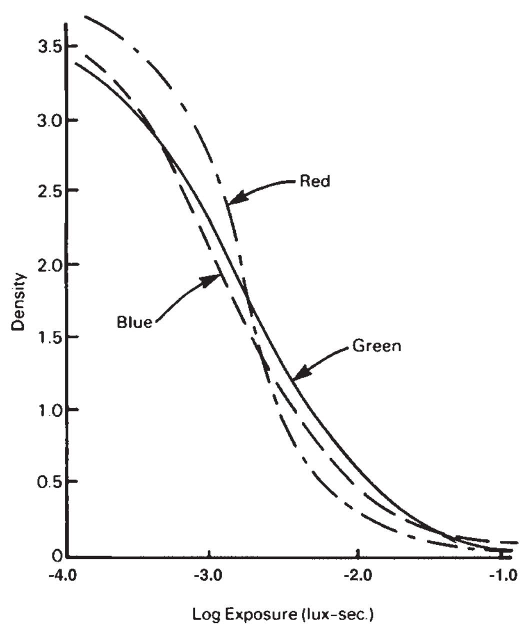


Figure 11-21 Red, green, and blue status A density curves from a non-neutral reversal color image. Since the red curve is significantly higher in the shoulder region, the shadows in the photograph would have a cyan cast. The highlights would show a reddish cast because the red curve is much lower in the toe region.

The speed of reversal color films is calculated from the average of the log exposures required to produce two different densities.

The term *crossed curves* refers to a lack of parallelism of the red-green-blue characteristic curves.

For example, Figure 11-21 illustrates the red, green, and blue status A curves for a second strip. The shape of the red density curve is considerably different from that in Figure 11-20—the principal difference being an increase in the gamma. Such a condition is referred to as crossed curves and is generally related to problems in the film processing. In this image, the shadows would probably appear somewhat cyan because of the high red density, and the highlights would likely contain a red cast because of the lowered red density (indicating less cyan dye) in that region. The resulting color transparency would likely have unacceptable color quality.

Figure 11-22 illustrates the red, green, and blue status-A curves for a third strip. In this case, the shapes of all three curves are approximately the same, except the blue density curve is displaced to the right. Thus there is an increase in blue density everywhere in the image. The image corresponding to the curves in Figure 11-22 would likely show an overall yellow-colored cast. Such an image could result from exposing a reversal color film balanced for daylight (5500 K) to a tungsten light source without the proper filtration.

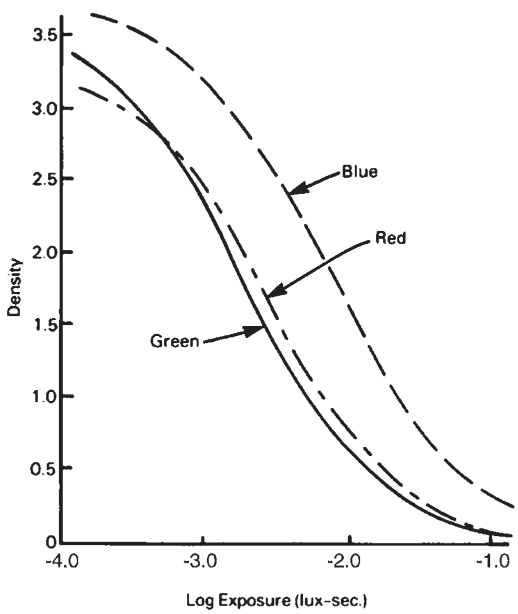


Figure 11-22 Red, green, and blue status A density curves from a non-neutral reversal color image. The image shows a high density to blue light in all regions and thus would appear yellow.

Negative Color Films

Examples of negative color films include Kodak PORTRA and ULTRA color films and Fujicolor Portrait and Press films. Color-negative films, sometimes referred to as color print films because prints are made from them, employ the traditional integral-tripack assembly. However, many modern-day films have double-coated emulsions in each of the three spectral bands to improve latitude and film speed. The spectral responses of the emulsions are selected principally for the ability to produce optimum color reproduction in the final color reflection print. Since the color negative represents only an intermediate step in the system, it makes no difference what the actual colors of the negative are, as long as they are matched to the properties of the color print material. This allows for the use of integral color masking, as discussed previously, which gives an overall orange cast to the negative.

The product of a set of neutral exposures and normal processing of the color negative material is a scale of non-neutral densities. The resulting sensitometric strip is evaluated by measuring the red, green, and blue densities on a densitometer equipped with the status M response functions. The red, green, and blue density plots for a sensitometric test of a typical negative color film are shown in Figure 11-23. The graph indicates that increasing

amounts of exposure give increasing amounts of density, as is the case for negative-working materials.

Additionally, the slopes of the three curves are considerably less than those of a reversal color film, resulting in an increase in the exposure latitude. The three curves are separated vertically, because of the orange-colored integral mask in the image. The minimum densities for the curves are located at the far left of the graph and consist of the integral mask density, emulsion fog, residual color couplers, processing stain, and base density. The density to blue light is always the highest of the three because of the principal absorption of the yellow dye, the blue absorption of the integral mask, and the unwanted blue absorptions of the magenta and cyan dyes. Since the yellow and magenta dyes have only low absorptions to red light, the density to red light is generally the lowest of the three, resulting mostly from the cyan dye. It is sometimes assumed, erroneously, that the blue curve is the highest because it is the top emulsion layer, and the red curve is the lowest because it is the bottom layer of the three. The order in which the emulsion layers are coated has absolutely no effect upon the red, green, and blue light-stopping ability of the image that is formed in the emulsion. This is a result of the nature of the dye set and the integral color mask in the color negative.

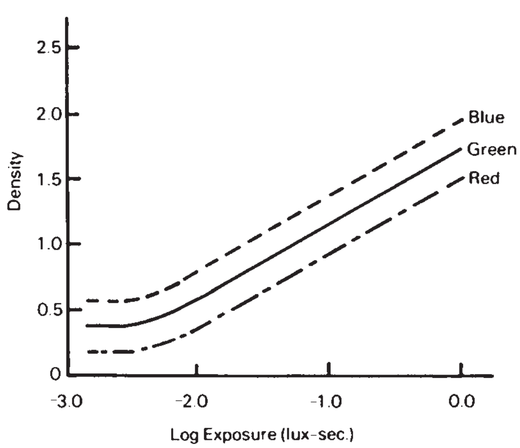


Figure 11-23 Red, green, and blue status *M* density curves from a neutrally exposed and processed negative color film. The integral color-correcting mask gives the image an overall orange cast, causing the curves to be vertically displaced.

The contrast of color-negative films is generally determined by measuring the slope of the straight-line portion (gamma), which typically lies between 0.50 and 0.60. As with the black-and-white negative-positive process, the color negative has a relatively low slope and large exposure latitude, allowing for a variety of subject contrast. The lowered slope of the negative is compensated for in the printing stage by using print materials with steep slopes. Theoretically, the slopes of the three curves should be equal over their entire length to avoid undesirable shifts in color balance between the shadows and the highlights. However, practical experience indicates that some divergence in slopes can be tolerated, depending to a great extent upon the nature of the scene.

The speed of a color negative film is derived from locating the minimum useful points (0.15 above the minimum density) on the green status *M* density curve and on the slowest of the three status *M* density curves. Since the slowest curve invariably is the red status *M* density curve, it is the green and red status *M* density curves that are used. The log exposure (in lux-seconds) at each speed point is determined and averaged. The antilog of the resulting log H value (H_m) is then used in the following formula (Eq. 11-2):

$$\text{Speed} = \frac{I}{H_m} \times 1.5 \qquad \text{(Eq. 11-2)}$$

The red-green-blue characteristic curves for typical color negative materials are displaced vertically because of the absorption of blue light and green light by the color-correcting mask.

The blue status *M* density curve is not used to determine film speed, because it is the fastest of the three and would produce a slightly inflated speed.

Since three filter color densities do not give precise information about either visual appearance or printing characteristics, such data for color negatives must be interpreted with the same care as discussed previously with reversal color images. Nevertheless, it is possible to make meaningful inferences about the printing properties when there are large differences between the aim curve shapes and those actually encountered. For example, the red, green, and blue status *M*-density curves in Figure 11-24 illustrate the sensitometric results of overdevelopment of a color negative. Comparing these curves to those shown in Figure 11-23 (normal processing conditions) reveals that the extended development time produces a noticeably higher contrast in the blue density plot.

Such a change in curve shape would lead to the problem of crossed curves, with the negative producing a color print with a noticeable color shift between the shadows and the highlights (that is, the shadows would have a yellowish cast, while the highlights would have a bluish cast). This problem can be illustrated graphically by superimposing the red, green, and blue density curves, which is essentially what happens when the negative is printed on conventional color print material using supplementary filtration in the enlarger.

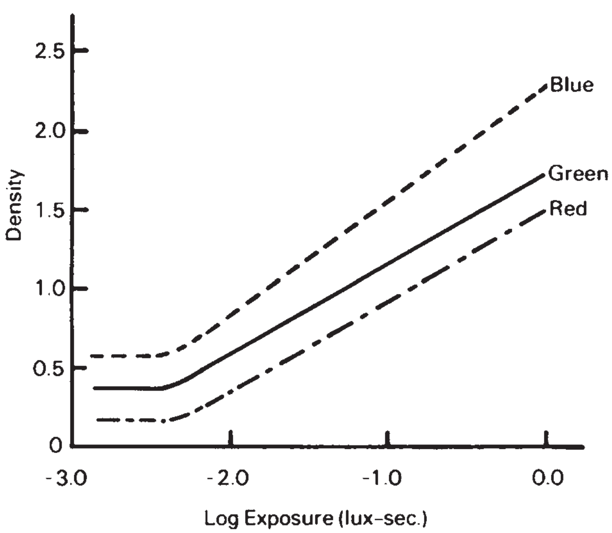


Figure 11-24 Red, green, and blue status M density curves from a neutrally exposed negative color film that was overdeveloped. Notice the increased slope of the blue density curve.

Figure 11-25A illustrates how the red, green, and blue density curves exactly superimpose for a normally exposed and processed color negative. Figure 11-25B illustrates what happens when an attempt is made to balance the color negative shown in Figure 11-24. Notice that the blue density curve is steeper, and if a midtone is printed to a neutral, as shown here, the blue light density in the shadows will be low, producing larger amounts of yellow dye in the print. The blue density in the highlights will be higher, resulting in a lack of yellow dye (a bluish cast) in the highlights. Thus when the red, green, and blue density curves are severely crossed, excellent color prints cannot be obtained.

Photographic Color Paper

In the other half of the negative-positive process, a color reflection print is made from the negative. Therefore, the properties of color photographic papers depend primarily upon the characteristics of the negatives to be printed. For example, the spectral sensitivities of the paper emulsions are typically matched to the spectral absorptions of the dyes in a color negative, thus allowing for optimum color reproduction. The inherent color

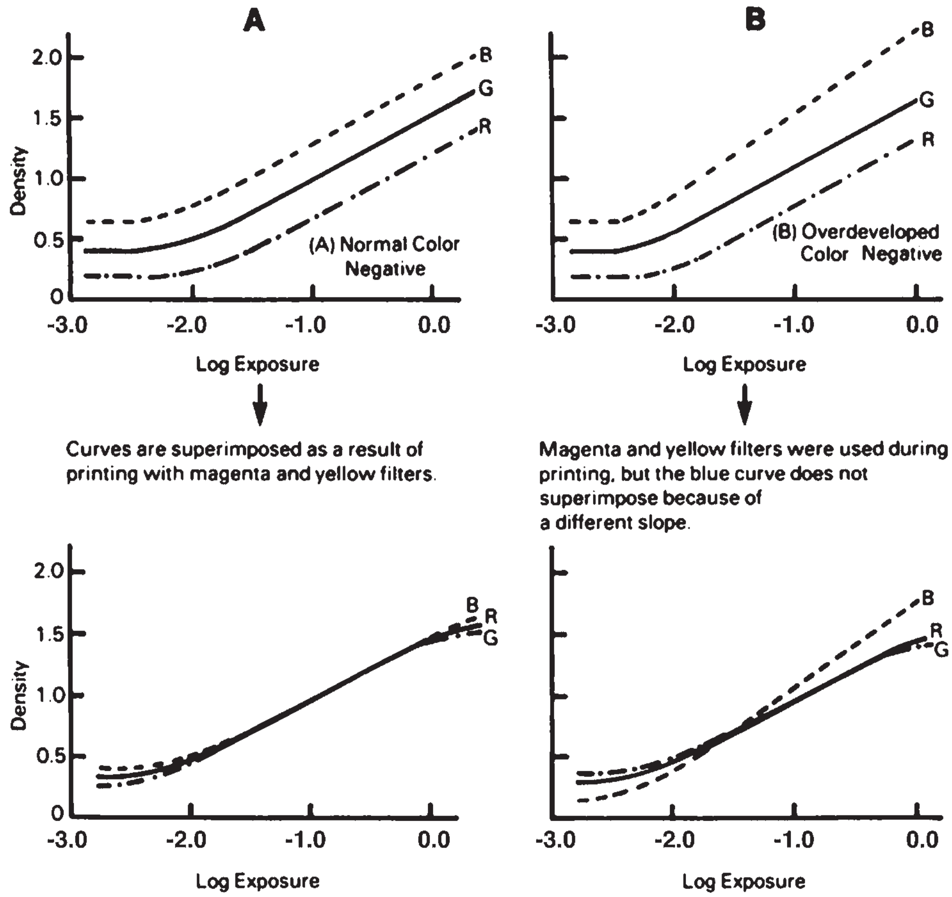


Figure 11-25 The sensitometric effects of printing color negatives in an enlarger using supplementary filtration. The curves in graph A are from a color negative with proper contrast in all three layers. The use of supplementary magenta and yellow filters in the printer brings the curves into nearly exact alignment, as shown at the bottom of graph A. The curves in graph B are from a negative with high blue contrast and normal green and red contrast. When this negative is printed, there is no combination of filters that can eliminate the mismatch seen in graph B, bottom.

balance of the color paper emulsion is designed so that using a tungsten enlarging lamp in combination with the red-, green-, and blue-light-stopping abilities of a typical color negative will result in a properly balanced color print with a minimum of supplementary filtration. Furthermore, by making the paper's red-sensitive layer the slowest, the use of supplemental cyan filtration with its unwanted absorptions can be avoided.

If a color reflection paper is exposed and processed to produce a scale of visual neutrals, the visual densities of the steps can be measured and a characteristic curve constructed as shown in Figure 11-26. Notice that the curve shape is very similar to that of black-and-white reflection print material. The steep slope in the curve's midsection is necessary to expand the midtones, which were compressed in the negative as a result of the lowered slope in the negative. The result is a print with the desired tone reproduction characteristics, as discussed in Chapter 6.

Notice that the maximum density of color paper is somewhat greater

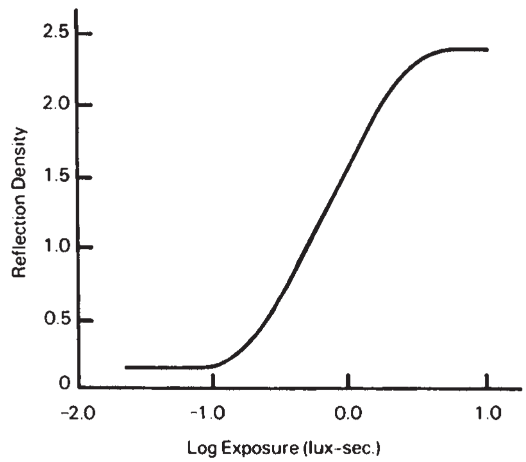


Figure 11-26 Visual density curve from a neutrally exposed and processed reflection color print material.

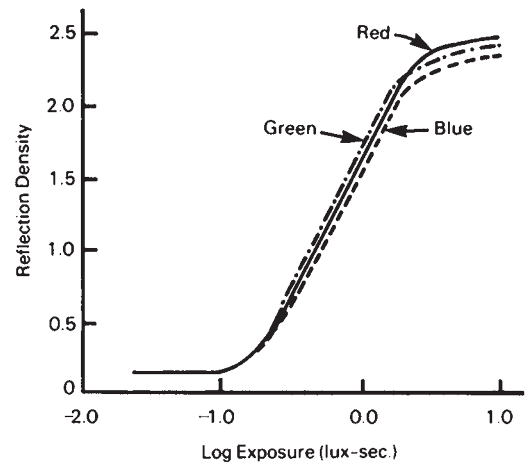


Figure 11-27 Red, green, and blue status-A curves from a neutrally exposed and processed reflection color print material. The image is a visual neutral.

The color sensitivities of the three emulsion layers of color printing papers are controlled during manufacture so that it will not be necessary to use the inefficient cyan filters when printing.

than that of a black-and-white reflection paper. This is principally due to multiple internal reflections between the emulsion layers in the color paper, which cause less light to be reflected from the print. Since there are no standard methods for determining the speed and contrast of color print materials, there exists no common method for determining these properties. However, since the characteristics of color and black-and-white reflection print materials are similar, the same methods may be used.

On this basis, the useful log exposure range for a conventional color reflection print material turns out to be approximately 1.15 to 1.25 (current ANSI standard paper range of 120), indicating that it is similar to a contrast grade 2 black-and-white printing paper. Also, the ANSI standard paper speed is approximately 100, indicating that this is a medium-speed paper. Such information is of little practical use, because color print materials are invariably balanced individually when the negative is printed. In effect, individual tests are performed for each negative/print combination, minimizing the need for standardized values of speed and contrast.

Figure 11-27 illustrates the red, green, and blue status-A density curves for the same scale of visual neutrals. Again, notice that the three curves are not exactly superimposed, indicating that a set of visual neutrals is not the same as a set of densitometric neutrals. The inherent sensitivity of the red, green, and blue layers is illustrated in Figure 11-28, where it can be seen that the blue-sensitive and green-sensitive layers are faster (displaced to the left) than the red-sensitive layer. This is in part to compensate for the integral mask incorporated in the negative, which has a high density to blue and green light. Also, because the tungsten lamps used in color enlargers are rich in red light, the paper speed in this region can be reduced.

Thus by matching the speeds of the three layers of the color print material to the red light, green light, and blue light stopping characteristics of the integral mask in the color negative, minimum amounts of supplementary filtration will be required to

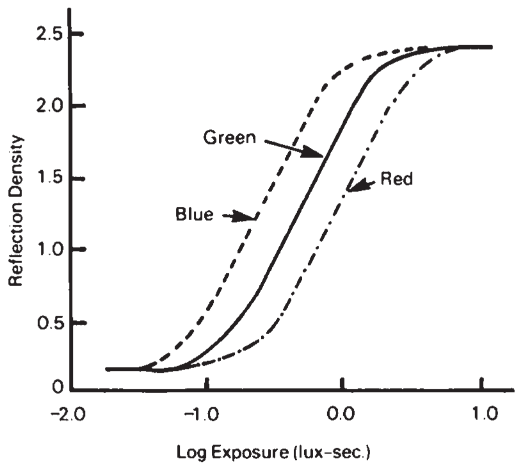


Figure 11-28 Red, green, and blue status-A curves from reflection color print paper balanced for an orange mask but printed without it. Thus the actual speeds of the three layers are revealed. The blue-sensitive and green-sensitive layers are the fastest, which compensates for the high blue and green densities of the orange negative mask.

obtain optimum color reproduction. In essence, the three curves illustrated in Figure 11-28 will be superimposed as they appear in Figure 11-27, as a result of the filtration caused by the integral orange mask and the supplementary filtration in the printer.

REVIEW QUESTIONS

1. The major physical reason why color photographs cannot exactly duplicate subject colors is that . . .

   A. photographic lenses alter the color balance of the image-forming light.
   B. there is variability in the processing of color films
   C. there is variability in the manufacture of color films
   D. existing dyes have limitations

2. The subtractive primary colors absorb . . .

   A. red, green, and blue light
   B. cyan, magenta, and yellow light

3. In comparison with daylight-reversal color films, tungsten-reversal color films have . . .

   A. relatively low red sensitivity
   B. relatively high red sensitivity
   C. about the same red sensitivity

4. The poorest of the three dyes, with respect to unwanted absorption, is the . . .

   A. yellow dye
   B. magenta dye
   C. cyan dye

5. A practical method of obtaining analytical densities with integral tripack color film such as Ektachrome is to . . .

   A. expose only a single emulsion layer.
   B. develop only a single emulsion layer
   C. expose and develop all three emulsion layers and then bleach the dyes in two layers
   D. isolate one of the three dye layers by using a filter on the densitometer

6. The illumination system in reflection densitometers is based on the assumption that when prints are displayed they are illuminated . . .

   A. directly from the front
   B. at an angle of 45 degrees
   C. uniformly from all angles

7. The gamma of reversal color films is typically about . . .

   A. 0.7
   B. 1.0
   C. 1.2
   D. 1.4
   E. 1.9

8. Assuming that the red, green, and blue curves for a reversal color film should be superimposed for a neutral color balance, a transparency represented by a set of curves with the red curve higher than the other two would appear too . . .

   A. red
   B. green
   C. blue
   D. cyan
   E. magenta

9. The gammas of negative color film curves are . . .

   A. somewhat lower than the gammas of reversal color films
   B. about the same as the gammas of reversal color films
   C. somewhat higher than the gammas of reversal color films

10. The color balance of color printing papers is controlled during manufacture so that when exposing the paper it is usually not necessary to use a . . .

    A. cyan filter
    B. magenta filter
    C. yellow filter

chapter

12 Visual Perception

Photograph by Sarah Priestap, Photojournalism student, Rochester Institute of Technology.

Post-Stimulus Perception

Some of the light now reaching the earth from distant stars and galaxies originated millions and even billions of years ago. Events being observed through powerful telescopes are not happening now but actually occurred long ago. Our visual system does not operate on real time even for events viewed at small distances. The delay between when light falls on the retina in the eye and the perception, although measurable, is extremely short and is of little importance. Perceptions that occur after light stops falling on the retina, however, are of considerable importance. Post-stimulus perceptions can be divided into categories including *persistent images, afterimages, aftereffects, eidetic images, visual memory*, and *imagination imagery*.

Laboratory studies indicate that *persistent images* last an average of approximately one-quarter second after the stimulus has been removed. If a slide of the letter A, for example, is projected on a screen in a darkened room and the presentation time is controlled with a shutter, the time cannot be made so short that the image cannot be seen, provided the luminance is increased proportionally so that the same total amount of light is available to the viewer. *Bloch's law* predicts that the visual effect will be the same for different combinations of luminance (I) and time (t) as long as the product (k) remains the same (Eq. 12-1). Like the photographic reciprocity law, however, Bloch's law is not valid for high- and low-light

Persistent images prevent us from seeing that motion-picture screens are dark when the projector moves the film from one frame to the next.

Bloch's law states the visual effect will be the same for different combinations of luminance and time assuming their product remains the same.

values. Perception occurs with short exposure times because the persistent image keeps the image available to the viewer for somewhat longer than the actual presentation time.

$$I \times t = k \qquad \text{(Eq. 12-1)}$$

Persistent images are essential to the perception of realistic motion-picture and television pictures. When motion-picture films are projected, it is necessary to darken the screen with a rotating shutter when the film is being moved from one frame to the next. The persistent image prevents the viewer from seeing the dark intervals, which would appear as flicker. Early motion pictures were sometimes referred to as "flicks" because they were shown at sixteen frames per second and flicker was obvious. Even at the current twenty-four-frames-per-second sound motion-picture speed, flicker would be objectionable without the use of a chopper blade, which produces three flashes of light for each frame, or seventy-two flashes of light per second.

Anyone who has photographed a television screen at a high shutter speed realizes that there is never a complete picture on the screen. The image is constructed sequentially with a scanning electron beam taking advantage of the effect of persistent images so the viewer sees a complete picture. Duration of the persistent image can vary depending upon several factors, including the image luminance level and whether removal of the stimulus is followed by darkness or by another image.

It would be reasonable to speculate that increasing image luminance would produce a stronger effect on the visual system, which would increase the duration of the persistent image, but the effect is actually the reverse. The increase in persistent image duration with decreasing luminance can be explained by comparing the visual effect with capturing a digital image at low light levels. If the sensor does not receive sufficient exposure at a selected shutter speed and a particular aperture setting, the exposure time must be increased in order to obtain a satisfactory image. The visual system in effect compensates for the lower image luminance by sacrificing temporal resolution and increasing the duration of the persistent image, which is the equivalent of increasing the exposure time.

We can illustrate this effect with motion-picture film being projected on a screen. If flicker of the intermittent image is just noticeable at a certain luminance level, reducing the luminance will increase the duration of the persistent image to include the time the screen is dark between flashes, and the flicker will disappear. In this example, the decrease in luminance can be in several ways, a smaller projector bulb can be used, the projector-to-screen distance can be increased, a gray screen can be substituted for the white screen, or the screen can be viewed through a neutral-density filter.

Whereas a persistent image cannot be distinguished from the image seen while the stimulus is still present, afterimages are recognized by the viewer as a visual anomaly. Afterimages are most evident when the eye is exposed to an intense flash of light. Looking directly at a flashtube when it is fired usually causes the viewer to see a vivid afterimage spot for some time. An afterimage can be formed with a stimulus having lower luminance, such as a white circle on a black background, by staring at it for a long time and then looking at a uniform surface (see Figure 12-1). One should never look at

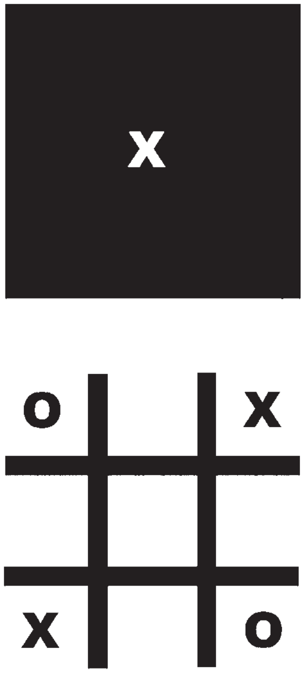


Figure 12-1 Afterimage. Stare at the isolated white X for about one minute. Then shift your gaze to the middle square and win the game of tic-tac-toe.

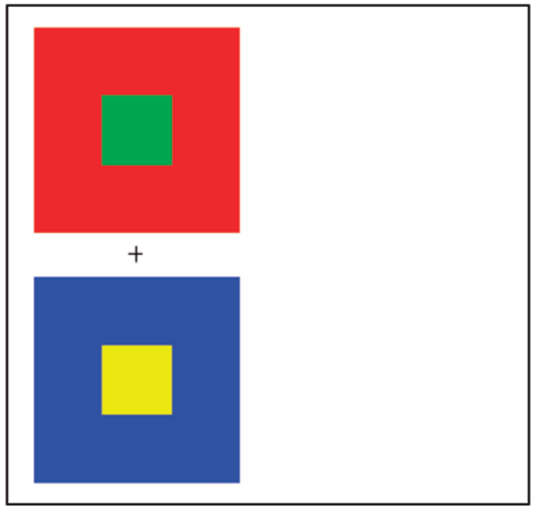


Figure 12-2 Color afterimages. Stare at the plus sign in the center of the two squares for about 60 seconds. Shift your gaze to the white adjacent area and see the squares' complimentary colors.

the sun, arc lights, UV sources, lasers, or other sources of radiation that can damage the retina.

Afterimages can be either negative or positive, but after looking at a bright stimulus, such as a lightbulb, the afterimage is typically dark (negative) if one looks at a white surface, and light (positive) if one looks at a black surface or closes and covers the eyes. Negative afterimages can be attributed to local bleaching of the visual pigments in the retina's receptors, positive afterimages to a continuation of the firing of the visual nerve cells. Negative afterimages of colored stimuli tend to be approximately complementary in color—a yellow lightbulb or other stimulus would tend to produce a bluish afterimage, for example. Colored afterimages can also be seen after looking at a white light source. If the red, green, and blue visual pigments in the cones are not bleached and regenerated at the same rate, a sequence of different colors may result, usually in the order of blue, green, and red. Figure 12-2 provides a demonstration of a color afterimage

Color afterimages can often be seen after looking at a bright white light source.

In contrast to persistent images, which contribute to the effectiveness of motion pictures by eliminating flicker, afterimages tend to interfere with subsequent perceptions. For example, an attempt to read immediately after looking directly at a flashtube when it is fired can be frustrated by the afterimage. When a visual perception is altered by a preceding visual experience, the alteration is referred to as an *aftereffect*. Whereas the afterimage of a yellow lightbulb tends to appear blue when the gaze is shifted to a gray surface, it tends to appear magenta when the gaze is shifted to a red surface. The perceptual result of mixing a blue afterimage with a red stimulus is similar to that produced by physically mixing blue and red light. If such an experiment is conducted to demonstrate an aftereffect, the viewer will be aware of the altered perception, but viewers are not commonly aware of aftereffects that occur in everyday

life. Brightness adaptation to daylight alters the subsequent perception of the light level in a dimly-lit interior, and it is only when the interior begins to lighten as the visual system adapts to the lower-light level that the viewer is aware of the aftereffect.

Aftereffects can alter the perception of other subject attributes besides color and lightness. Watching continuous motion in one direction, such as a waterfall, can cause stationary objects to appear to move in the opposite direction due to the aftereffect. Similarly, a rotating spiral design that appears to be expanding will appear to shrink when the rotation is stopped after prolonged viewing. Figural aftereffects are changes in the size, shape, or orientation of a perception as the result of a preceding visual experience. Fixating on a set of curved lines for a minute or so will tend to make straight lines appear to be curved in the opposite direction. The reader can experience a figural aftereffect with the drawing in Figure 12-3. After looking steadily at the X above the curved lines for a minute or so and then shifting the gaze to the X above the straight lines, the straight lines tend to appear to be curved in the opposite direction.

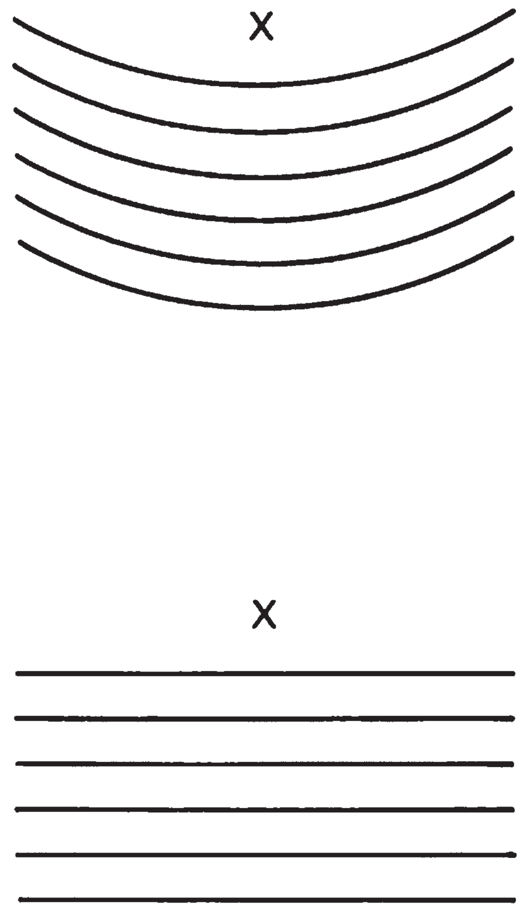


Figure 12-3 Figural aftereffect. After looking steadily at the X above the curved lines for a minute or so and then shifting the gaze to the X above the straight lines, the straight lines tend to appear curved in the opposite direction.

According to one study, approximately one in 12 young children has photographic memory capabilities.

Eidetic imagery, which is sometimes referred to as photographic memory, is an ability to retain a visual image for half a minute or longer after a stimulus has been removed from view. A 1968 study by Haber and Haber indicated that approximately 16 of 200 elementary schoolchildren experienced eidetic imagery. Since eidetic imagery is rare in mature adults, it is believed to decrease with increasing age. Eidetic imagery enables the viewer to read a printed page word-for-word and to see details in a complex picture for some time after removal of the printed page or picture. Whereas afterimages move with the eye, eidetic images remain stationary so that they can be scanned. Some persons who do see eidetic images are not aware of this capability because the experience seems normal to them, and they assume that everyone has the same experience.

Visual memory shares many characteristics with other types of memory, but it consists of an ability to retain or to recall a visual image that is distinct from persistent images, afterimages, aftereffects, and eidetic images. Visual memories are usually divided into two categories—short-term and long-term. Just as a new telephone number can be remembered long enough

to dial it by repeating it and keeping it in the conscious mind, so can a visual image be remembered for a short time by keeping it in the conscious mind. Experiments indicate that most people cannot retain more than five to nine independent pieces of information, such as numbers in random order, in short-term memory.

A person should not expect to remember, even for a short time, all of the details in a complex picture. Instead, a person tends to remember the details that attract the most attention or hold the most interest. Short-term visual memory is used even as someone scans a picture and fixates different parts of the image, and this enables the viewer to create a composite perception of the total picture.

Once the attention is allowed to go on to other things, long-term memory is required to revive an earlier visual image. If people are asked to indicate how many windows are in their home or apartment, they will use visual memory to form an image of the interior and then mentally move around it and count the windows. Some visual memories can be recalled easily, but those stored in the subconscious mind are more elusive and may require the use of special techniques such as hypnosis or association. Various procedures for testing visual memory include the use of *recognition*, where the subject selects the one picture of several that most closely resembles the original stimulus. Another procedure, known as the *recall* method, is to ask the person to describe the original scene from memory or to draw a picture of it. Visual memory can be improved by several methods, such as using attention to produce a more vivid perception, keeping short-term memories in consciousness longer through rehearsal, and practicing making sketches from memory.

Except for simple stimuli such as a circle or a square, visual-memory images generally are not facsimile representations of the original scene, but rather they usually contain just the more important details.

Imagination imagery, on the other hand, may bear no resemblance to any single earlier visual experience. Just as a writer can write a fictional story, so can a person create a fictional visual image that is as vivid as a visual memory of an actual object, scene, or event. Artists use imagination imagery when they draw or paint pictures of something that does not exist—a pocket watch flowing over the edge of a table in a surrealistic Salvador Dali painting is a dramatic example.

Photographers also use imagination imagery when they previsualize a finished picture, possibly even including a subject, props, background, arrangement, lighting effect, and colors (see Figure 12-4). Imagining impossible images has been recommended as an exercise for developing creative imagination, such as visualizing a large building

Film editors depend heavily on both short-term and long-term memory.

Figure 12-4 Previsualizing a finished photograph, such as this one, before making it, involves imagination imagery. (Photograph by Les Stroebel.)

Photographers make use of imagination imagery whenever they previsualize a finished picture.

White, gray, and black are colors that are properly identified as neutral colors.

Color photography is based on the subtractive primaries: cyan, magenta, and yellow.

Color television is based on the additive primaries red, green, and blue.

jumping around like a bird, the water in Niagara Falls moving up rather than down, or a full moon shrinking in size and then disappearing.

Perception of Stimulus Attributes

If one were required to describe precisely to another person the appearance of an object, using only words, it would be necessary to analyze the object's appearance in terms of attributes such as shape, color, and size. Different authorities on visual perception often disagree about the critical stimulus attributes for visual perception, the relative importance of each, and even the definitions of the terms. For example, the word *form* generally implies different object qualities to artists and photographers. Six attributes considered especially important to photographers will be discussed here: color, shape, depth, size, sharpness, and motion.

Color Hue

To accurately describe or identify a color, three different qualities of the color must be considered—hue, lightness, and saturation. *Hue* is the quality associated with color names such as red, green, blue, cyan, magenta, and yellow. White, gray, and black are also colors, but they are all neutral—without hue. Neutral colors are sometimes referred to as *achromatic colors*.

Color hues are commonly associated with names, such as red or green. Problems in communicating specific information about colors will occur unless everyone uses the same names for the same colors. Unfortunately, many children have learned that the names of the primary colors of watercolors used for painting are blue, red, and yellow, rather than the correct names of cyan, magenta, and yellow. Advertisers have not helped matters by using exotic-sounding or unusual names for colors rather than more common and descriptive names. Color-notation systems such as the Munsell system have done much to bring order to the identification of colors. The Munsell system uses five basic hues: red, yellow, green, blue, and purple. The complete Munsell hue circle, which includes subtle transitions between adjacent hues, has 100 hues, which is about the maximum a person with normal color vision can distinguish in side-by-side comparisons.

Much of the discussion about color as it relates to color photography can be accomplished with combinations of the three additive primary colors: red, green, and blue. Combinations of pairs of these colors of light produce cyan, magenta, and yellow, which are called additive secondary colors or subtractive primary colors. The relationship of these six hues is often represented in the Maxwell triangle, shown in Figure 12-5.

Red, green, and blue are identified as *additive primary* colors because by combining red, green, and blue light in different proportions it is possible to produce almost any color, including neutral colors. Cyan, magenta, and yellow are identified as *subtractive primary colors* because dyes and other colorants in these hues absorb

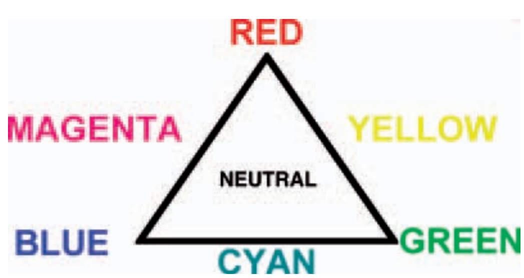


Figure 12-5 The Maxwell color triangle.

red, green, and blue light, respectively, from the white viewing light. Perceptually, however, primary colors are defined as those hues that appear to be pure rather than a mixture of other hues. In this sense, red, green, blue, and yellow are primary colors, and they are identified as *psychological primary colors*. Including the neutral pure colors of black and white increases the number of perceptual primary colors to six.

Persons having normal color vision are identified as *normal trichromats*, based on the three types of cones in the retina, which are sensitive to red, green, and blue light. Not all normal trichromats, however, respond to colors in exactly the same way. For this reason, scientific studies of color vision make use of the average response of a number of persons having normal color vision.

There are a number of types of defective color vision. A person who is missing one of the three types of cone pigments is known as a *dichromat*. *Monochromats* are missing two of the three cone pigments (or possibly have rhodopsin, the rod photopigment, in the cones). *Dichromats* have difficulty distinguishing between red and green, or more rarely between blue and yellow. There are very few monochromats, but their vision is the equivalent of black-and-white photography.

The red, green, and blue cone sensitivities suggest a simple trichromatic theory of color vision, but much of the experimental evidence supports the opponents' theory of color vision, whereby information from the red-, green-, and blue-sensitive cones is thought to be transmitted in combinations—specifically red-green, blue-yellow, and black-white—through three separate channels.

Other than missing one or two of the three types of cone photopigments, defective color vision can also be associated with reduced sensitivity of one or two of the three cone types, or with a shift in sensitivity along the spectrum for one or more of the cone types. People who have all three types of cone photopigments but who do not have normal color vision for either of the reasons cited are referred to as *anomalous trichromats*—as distinct from the conventional trichromats, dichromats, and monochromats.

Additive primaries are red, green, and blue.

Subtractive primaries are cyan, magenta, and yellow.

A person with normal color vision may have inaccurate perception of stimulus colors under certain conditions. Some of these conditions are (a) when the image is formed near the periphery of the retina, (b) when the light level is very low or very high, (c) when the stimulus is very small in area, (d) when the stimulus is presented for a very short time, (e) when the stimulus is illuminated with other than white light, and (f) when the viewer is adapted to a different color. Accurate color identification requires normal color vision, standard viewing conditions, and the opportunity to make side-by-side comparisons with standard colors.

Heredity is responsible for most cases of defective color vision, although it can result from other causes such as the use of certain drugs, excessive use of alcohol, and brain damage. About 8 percent of white males and 0.4 percent of females of all races have some form of defective color vision. There is no cure for congenital defective color vision. Some people whose occupations require being able to discriminate between certain colors have been helped by using filters of different colors over the left and right eyes. Photographers with defective color vision are able to make color prints

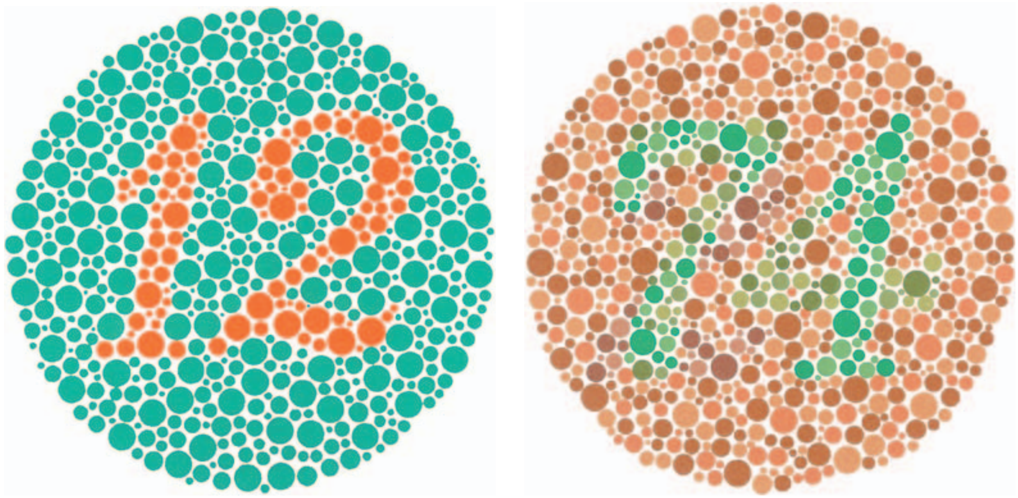


Figure 12-6 Ishihara color plates: A person with normal color vision or a color blind person will see "12" in the plate on the left, whereas a person with normal color vision will see "74" on the right and a dichromat or anomalous trichromat will see a "21."

that are acceptable to themselves, but the prints often do not appear correct to people with normal color vision.

Defective color vision can be detected with various types of tests. One test, the Ishihara pseudoisochromatic plate test, contains either simple geometric designs or numbers made up of colored circles against a background of gray circles (see Figure 12-6). People with defective color vision are unable to see some of the designs that are visible to persons with normal color vision. Another test, the Munsell 100-Hue test, requires the subject to arrange color samples that vary in hue in the correct order to provide a consistent transition. This test can also determine how well people with normal color vision can make small discriminations between colors. With this test, defective color vision is revealed by large errors with certain hues, whereas low discrimination is revealed by randomly distributed errors with all hues.

A glossy photographic print has a density range of about 2.0. This is a luminance ratio of 100:1.

Everyone is color blind under certain conditions, such as when the light level is very low.

Color Lightness

Luminance ratios as low as 100:1 in a photographic print can create the perception of tonal differences of white and black. This fact is misleading with respect to the ability of the visual system to detect differences in lightness (reflected light) or brightness (light sources) over a wide range.

Viewing transparencies or projected slides in a darkened room requires a somewhat greater luminance ratio to produce the perception of a range of tones from white to black—approximately 500:1 (see Figure 12-7). Since reversal color films typically produce a maximum density of over 3, it is possible to obtain a luminance ratio of 1000:1 in the image, compared to a maximum density of approximately 2 in typical photographic papers. Placing one gray scale in direct sunlight and a second gray scale in the shade on a clear day when the lighting ratio is about 8:1 produces a luminance ratio of approximately 800:1 between the light end of the gray scale in sunlight and the dark end of the gray scale in the shade. A person may be able to see the separation between all steps on both gray scales caused by local adaptation, whereby sensitivity of the visual system is increased in darker areas and decreased in lighter areas.

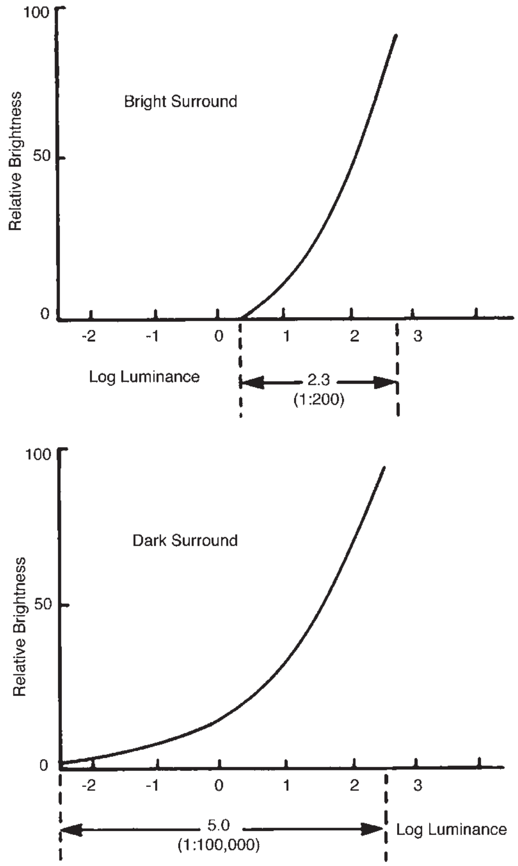


Figure 12-7 Curves representing the perception of brightness in relation to subject luminance with a bright surround (top) and dark surround (bottom). The difference in the log luminance ranges indicates that higher contrast photographic images are required for projection viewing in an otherwise darkened room than for viewing with normal room illumination.

When general adaptation is taken into account, the ratio of luminances over which the visual system responds is truly amazing. A white object in sunlight has a luminance of approximately 100 million times that of a white object in starlight, and yet both can be seen quite easily when a person is fully adapted to each light level. Under optimum laboratory conditions, a person can detect a flash of light having a luminance of only 1/100 that of white paper in starlight, and when adapted to bright light a person can detect luminance differences up to 1000 times that of white paper in sunlight, which is approaching luminances that can be damaging to the retina. Thus the total response range of the visual system is approximately 10 trillion:1, or a log luminance difference of 13.

To appear correct in contrast, slides and transparencies viewed in a darkened room must have higher contrast than photographs viewed under normal room illumination.

It is important to make a distinction between *luminance*, which is psychophysical and measurable with a light meter, and the perception of *brightness* (or *lightness*), which is influenced by physiological and psychological factors and is not directly measurable. The eye is not a dependable instrument for measuring luminance values. For example, it is difficult for a person to judge whether a black surface in direct sunlight is reflecting more or less light than a white surface illuminated with lower-level incandescent light indoors, because of two variables—reflectance of the two surfaces and the amount of light falling on them. The adaptation level of the visual system can affect perception in that a surface with a fixed luminance will appear lighter when the eye is dark adapted than when it is light adapted. Also, a gray tone appears lighter in front of a black background than in front of a white background, an effect known as lateral adaptation or simultaneous contrast.

The eye, however, is very good as a null instrument where very small luminance differences can be detected in side-by-side comparisons. Thus, visual densitometers can be quite accurate where the sample being measured is seen in a circle surrounded by a ring that can be adjusted to match the inner circle in brightness (see Figure 12-8).

It is more difficult to match the brightness or lightness of two areas if they differ in hue. If, for example, the inner circle in a visual densitometer is red and the outer ring is blue, the operator will have more trouble judging when the two match in brightness.

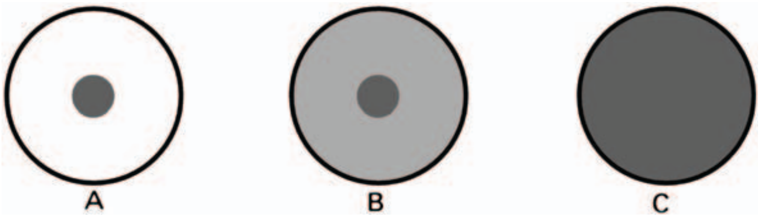


Figure 12-8 Field of view in a visual densitometer. (A) Dark small circle is the unknown density of the sample. The larger circle is the matching field set at 0 density. (B) The density of the matching field is increased but is insufficient to match the density of the sample. (C) More density is added to the matching field and it now matches the density of the unknown sample. The known density of the matching field now becomes the density of the sample.

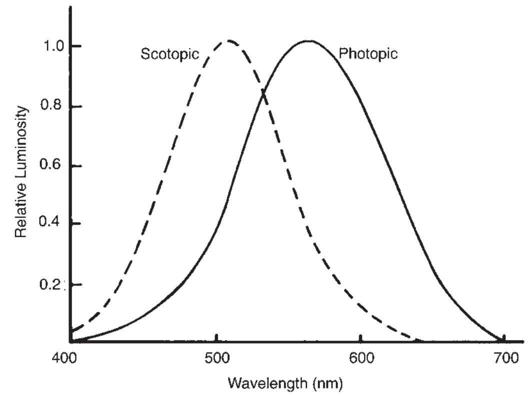


Figure 12-9 Photopic (P) and scotopic (S) response curves for the human eye.

The human eye is a good measuring instrument only when making comparisons.

A Wratten 90 filter is used for visualization by Zone System photographers.

Color saturation is the extent to which a color differs from gray.

When it is important to match the brightness of samples having different hues, a device called a flicker photometer can be used to present the two fields to the viewer alternately in rapid succession. When the two do not match closely in brightness, a flicker is seen. It is important for photographers to develop some skill in judging the lightness of subject colors so that they can anticipate whether there will be tonal separation in black-and-white photographs, such as in a photograph of a red object in front of a blue background made on panchromatic film. Some photographers use viewing filters in an effort to deemphasize hues and thereby make lighting effects easier to see.

Equal amounts of light of different wavelengths do not generally appear equally bright. With light levels high enough for the retinal *cones* to function—*photopic vision*—the greatest sensitivity is at a wavelength of approximately 555 nm, which is usually identified as green-yellow (see Figure 12-9). Since there is some variation among persons with normal vision, the luminosity function curve, or the American Standard Observer, is based on the average of a number of observers with normal color vision. With low light levels where only the rods function—*scotopic vision*—peak sensitivity shifts to a wavelength of about 507 nm. This change is known as the *Purkinje shift*, and can cause two colors, such as blue and red, that match in lightness when viewed in bright light to appear different in lightness when viewed in dim light, with the blue appearing lighter.

It is convenient to think of the limits of the visual system's response to electromagnetic radiation as being 400 nm and 700 nm. Although responses beyond these values are somewhat limited, 380 nm and 770 nm are more accurate limits, and responses have been detected as low as 300 nm and as high as 1050 nm. The cutoff on the low end tends to increase with age as the transparent material in the eye becomes more yellow and absorbs more ultraviolet and blue radiation.

Color Saturation

Saturation is the third dimension of color. It is defined as the extent to which a color departs from neutral. Thus grays have no saturation, and spectral colors have high saturation. The saturation of pure blue light can be reduced by adding either white light or yellow (the complementary color of blue) light, and the saturation of a blue dye or other colorant can be reduced by adding a gray or yellow colorant.

It is difficult for a person to judge the saturation of a color seen in isolation except in general terms such as low, moderate, and high saturation. In side-by-side comparisons, where the eye functions as a null instrument, it is easy to detect small differences in saturation provided the two samples match in the other two attributes—hue and brightness/lightness. The smallest difference that can be detected in saturation, or any attribute, is called a *just-noticeable difference* (JND).

Whereas there are upper and lower limits to the ability of the eye to detect changes in brightness, and limits at both ends of the visible spectrum with respect to seeing different wavelengths of electromagnetic radiation or hues, there are no limitations of the visual system at the lower and higher ends of the range of saturations of stimulus colors. Indeed, it has been a problem over the years to obtain primary-color dyes, inks, and other colorants with sufficient saturation to reproduce subject colors satisfactorily in photographic, photomechanical, and other images. Color masks in negative color films and black ink images in four-color photomechanical reproductions are compensations for the limited saturation of the dyes and the inks. The most saturated color of a specific hue and lightness that can be reproduced with a given system is called a *gamut color*. Gamut is also used to identify the full range of colors that can be produced with different combinations of the primary colors with a given system.

The perceived saturation of a given color sample can vary depending upon a number of factors. A blue sample will appear more saturated when viewed in front of a yellow background than in front of a gray background, and it will appear less saturated when viewed in front of a blue background of higher saturation. Whereas large juxtaposed areas of yellow and blue enhance one another's perceived saturation—an effect known as *simultaneous contrast*—the opposite effect can result when small areas of the same two colors are closely spaced in a picture or design. In this configuration, the colors tend to neutralize each other, an effect known as *assimilation*. Viewing large areas of complementary colors, such as blue and yellow, in sequence rather than simultaneously will also increase the perceived saturations, an effect known as *successive contrast*. Prolonged viewing of a color sample will decrease the retina's sensitivity to that color and cause it to appear less saturated, an effect known as *chromatic adaptation*. Shifting the gaze to a neutral surface will tend to produce an after-image that is approximately complementary in hue.

Color-temperature variations in viewing lights can produce either an increase or a decrease in the perceived saturation of colors. A decrease in the illumination level can produce a decrease in the appearance of saturation, and in dim light where only the rods function, even saturated colors tend to appear neutral. For the same reason, colors appear most saturated when viewed directly so that the images fall on the fovea of the retina, where the concentration of cones is highest.

It is also possible to induce the perception of hues with low to high saturation in neutral subjects. The color afterimage produced with prolonged viewing is one example. Chromatic sensations can also be produced when black-and-white images are presented to a viewer intermittently at frequencies of about five per second, when certain black-and-white designs are rotated at appropriate speeds, and even

Under the proper conditions, hues such as blue and yellow can be seen when looking at a black-and-white image that is illuminated with white light.

with certain stationary black-and-white designs that are viewed continuously, where the involuntary small-scale *nystagmus* movements of the eyes produce the necessary interactions in the visual response mechanism. These perceptions of colors in neutral stimuli are known as *subjective* colors or *Fechner's* colors.

Figure 12-10 The profile of George Washington, even though camouflaged, is easily recognized in this picture by Henry Inman. (Courtesy of the Metropolitan Museum of Art, New York City, New York.)

Shape

The word *shape*, as applied to an object, refers to its outline. Silhouettes emphasize shape and eliminate or deemphasize other attributes such as color, form, and texture. We depend heavily upon the attribute of shape for the identification of many objects, and often that is the only attribute needed for a viewer to be able to recognize the object in a drawing or photograph.

Three-dimensional objects actually have many shapes because each can be viewed from many different angles. The choice of viewpoint selected by a photographer to provide the best shape for an object being photographed is important even when the object is lit to provide detail, but it becomes critical in a silhouette. Silhouettes of people are commonly recognizable only in a full left or right profile view; thus profile views are normally used for the images of famous people on coins. Figure 12-10 shows an early American print in which George Washington is memorialized with an embedded profile between two trees.

Photographers can control the emphasis on object shapes by controlling the separation or contrast between object and background. The term *figure-ground* is commonly used to refer to the subject of a picture and the surrounding area. Figure-ground is an important concept in Gestalt psychology, where the emphasis is on the perception of the whole rather than an analysis of the parts. Experienced photographers have little difficulty separating an object from the background (figure from ground) in a photograph by means of choice of background, lighting, depth of field, etc. In military camouflage the objective is to conceal the shapes of objects so that they appear to be part of the background and therefore escape detection. In pictorial photography it is often just as important to de-emphasize shape in certain areas of a photograph as it is to emphasize it in other areas, and the principle of camouflage can be used for this purpose.

Although it is sometimes difficult to see the shape of an object clearly when it is not well separated from the background, we are seldom confused as to which is the object and which is the background when we can see both, either with actual objects or in photographs of objects. It is not difficult, however, to make simple drawings in which

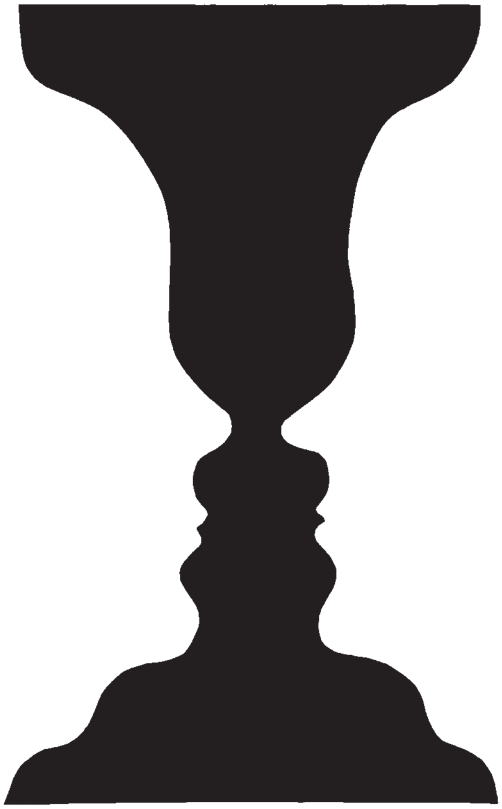


Figure 12-11 Rubin's figure, an ambiguous picture where the center area can be seen either as a vase or as a background for two profiles.

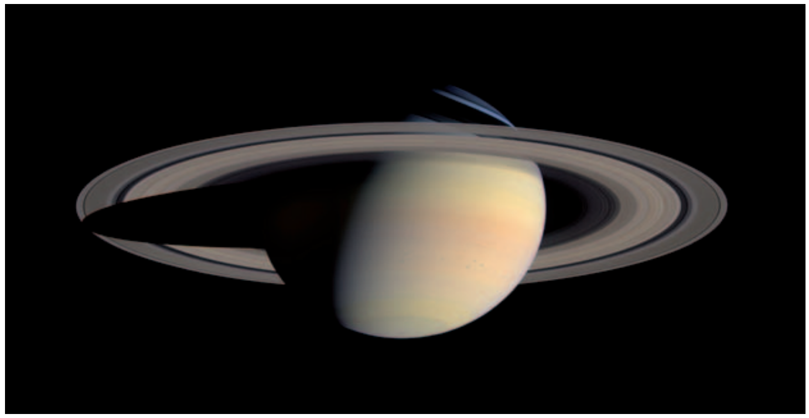


Figure 12-12 This photograph was taken by the Cassini Orbiter on October 10, 2006 from a distance of 3.9 millions miles. (Courtesy of NASA.)

a given area can be seen alternately as figure and as ground. In a famous Rubin ambiguous picture, for example, the center area can be seen either as a vase (figure) or as a background for two profiles (see Figure 12-11).

It is usually unnecessary to see the entire outline shape of a familiar object in order to be able to identify it and to visualize its entire shape. Most people, for example, perceive the moon as being round, not only when there is a full moon but also when there is a half-moon or quarter-moon and the shadow side cannot be separated from the background (see Figure 12-12). One can conduct a simple experiment by looking at objects outdoors through Venetian blinds, starting with the slats in the full open position and then gradually closing them to determine how small the openings can become before encountering difficulty in identifying the objects. A small number of dots arranged in a circular pattern can easily be seen as representing a circle. In Gestalt psychology, this effect is known as the principle of closure, in which the viewer mentally fills in the spaces between the picture elements. A distinction should be made, however, between closure, and fusion, where the optical-retinal system in the eye cannot resolve the small discrete elements as in a halftone reproduction or a photographic image at a small to moderate magnification.

Reading provides an excellent example of how the mind fills in spaces between fixation points. The area of sharpest vision represented by the fovea of the retina is very small, so that when a person fixates one letter in a line of type, only a few letters on each side can be seen clearly. The reason it is possible to read rapidly with only two or three fixations per line is that the reader recognizes groups of letters as familiar words without examining each letter, and can understand the meaning of a sentence without examining each word. Printed material that contains unfamiliar words and a high concentration of factual information

Figure and ground can be seen to switch places in certain so-called "ambiguous" images.

requires more fixations per line. Eye-motion studies have provided valuable information concerning reading, and how we look at photographs and other pictures. Viewers of pictures rarely scan them as thoroughly as they would a printed page, but rather fixate a few points in the picture and let the mind fill in the shapes and details between the fixation points.

The accuracy with which we perceive shapes is important in the study of visual perception, but it is not considered as critical in our daily lives as normal color vision and good acuity—which are usually tested before a person can obtain a driver's license or be permitted to perform certain occupational tasks. It has been demonstrated that it is easy to deceive a viewer about shape under certain conditions, A straight line, for example, can be made to appear curved, as shown in Figure 12-13. Under normal conditions, however, we are best able to detect changes in images having simple geometrical shapes such as straight lines, squares, circles, and triangles (see Figure 12-14). We are also better at making comparisons with superimposed or side-by-side images than with images that are separated in time or space, where memory becomes involved.

The perception of shapes is complicated by the fact that image shape changes with the angle and distance of the object relative to the eye or the camera lens. Parallel subject lines are imaged as converging lines except when viewed or photographed perpendicularly, and tilted circles are imaged as ellipses. Through experience we have learned that the parallel lines and circles do not change shape with a change in viewing angle, so we mentally compensate for linear perspective effects. *Shape constancy* refers to this stability of the perceived shape of objects as the viewing or camera angle changes.

Shape constancy causes tilted circles to be perceived as tilted circles rather than as ellipses.

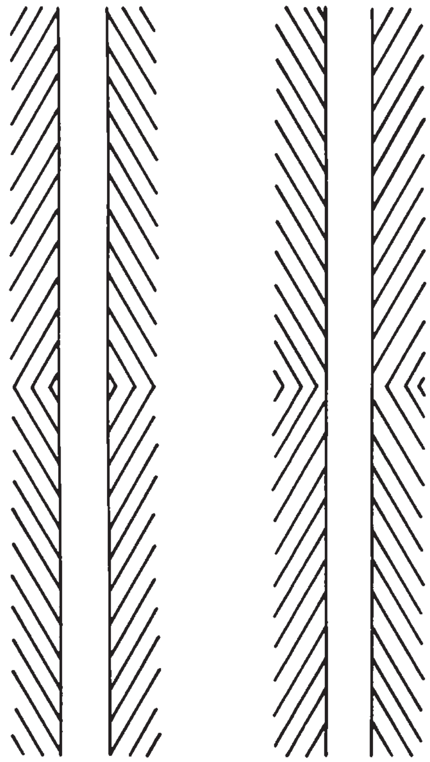


Figure 12-13 Illusory figures. The long straight lines tend to appear curved because of the influence of the diagonal lines.

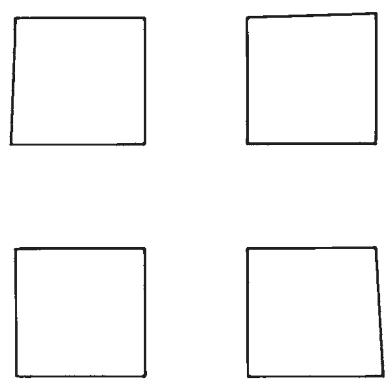


Figure 12-14 Which is the perfect square?

Shape generalization is the tendency to perceive an irregular shape as a simpler shape—obtuse and acute angles seen in perspective may be perceived as right angles, and an ellipse seen in perspective may be perceived as a

Figure 12-15 The principle of shape generalization causes the ellipses in this image to be generally perceived as perspective views of circles. (Photography by Jessica L. Scott, Imaging and Photographic Technology student, Rochester Institute of Technology.)

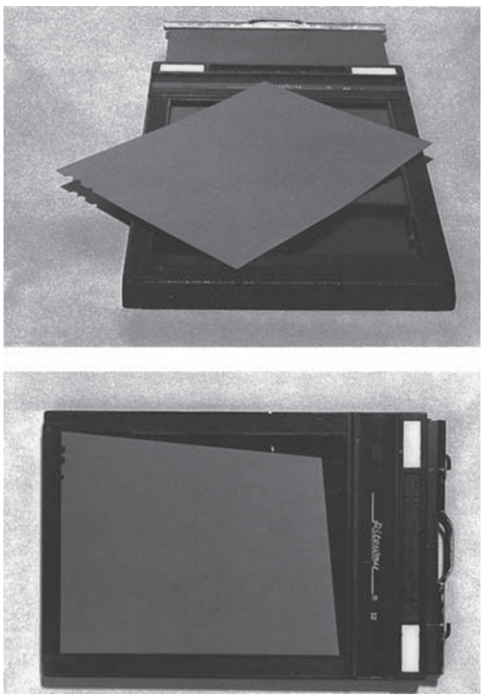


Figure 12-16 When the sheet of film in the top photograph is viewed obliquely, it is perceived as being rectangular, because of shape generalization, even though the perpendicular view in the bottom photograph reveals that the film has only one 90° corner.

circle (see Figures 12-15 and 12-16). Memories of perceived shapes can also change with time. The simplification of irregular shapes because of memory is called leveling; the exaggeration of a distinctive feature, such as a small gap in an otherwise continuous line, is called *sharpening*.

Size

The perceived size of an object has little relationship to the size of the image on the retina.

The perceived size of an object has little relationship to the size of the image on the retina (or the size of the image in a photograph of the object). An automobile, for example, is judged to be about the same size when viewed over a wide range of distances—an effect known as *size constancy*. Experiments have demonstrated that the accuracy of judging the size of an abstract shape, such as a circle, depends greatly upon being able to estimate the distance. As distance cues are systematically eliminated, the accuracy decreases.

When the precise size of an object must be known, a ruler or other measuring instrument is used for a direct side-by-side comparison. As with the perception of other object attributes, the eye is most precise when used as a null instrument in making comparisons between adjacent stimuli. It is sometimes necessary to include a ruler beside an object in a photograph when it is important to be able to determine the size of the object, as in some forensic photographs. In pictorial photographs, it is usually sufficient to include an object of known size with the unfamiliar object, and to provide good distance cues.

It is not difficult to deceive a viewer about the size of objects represented in photographs. Use of a short focal-length camera lens tends to make foreground objects appear larger than normal and background objects appear smaller than normal when the photograph is viewed at a comfortable distance, and long focal-length camera lenses have the reverse effect. Line drawings can

The moon is commonly perceived as being larger when it is near the horizon than when it is overhead.

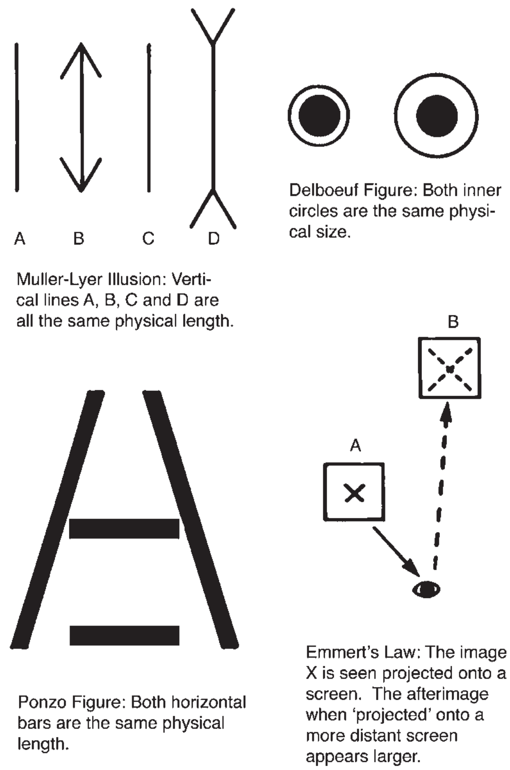


Figure 12-17 Size/distance constancy. For familiar objects, size and distance are inseparable. For an object to be the same actual size at a farther distance it has to be larger, and therefore it appears to be larger. (The moon illusion is yet another example of this phenomenon.)

also cause viewers to misjudge the relative length of lines or size of images. The Muller-Lyer arrow illusion and the Ponzo railway lines illusion both contain lines of equal length that are perceived as being unequal (see Figure 12-17).

In nature, the moon is commonly perceived as being larger when it is near the horizon than when it is overhead. Various explanations of this illusion have been offered, but the most acceptable one is that the moon is thought of as being farther away when it is near the horizon, as an airplane would be, so that when the retinal image remains the same size as the moon moves toward the horizon from overhead it is perceived as being a larger object farther away. *Emmert's law*—that the size of an afterimage increases in proportion to the distance to the surface onto which the image is projected—supports this explanation.

Visual Acuity

As an object of moderate or small size is moved farther away from a viewer and the retinal image decreases in size, a point is reached where the viewer is no longer able to see the object. *Visual acuity* is a measure of the ability of a person to see detail. Visual acuity tasks are commonly classified as detection, localization, recognition, and resolution, with different types of test targets used for each task. A black dot or a black line on a light background can be used to measure detection. It is usual to measure the visual angle subtended by the appropriate dimension of the test target, rather than specify both the target dimension and the distance. A person with normal vision may be able to detect a black line having a width that represents a visual angle of only 1/120 of a minute (1/7200 of a degree). Visual acuity is the reciprocal of this angle in minutes, or 120. This value corresponds to a 1/4-inch black line, the thickness of a lead pencil, at a distance of 4/5 of a mile.

Localization is the ability to see where the opening in a Landolt C or the vernier displacement between two straight lines is located. Maximum acuity for the vernier lines is about 30, or about one-fourth the acuity for the detection of a black line.

Snellen eye charts containing letters of the alphabet of varying size are commonly used for eye examinations to test vision. Maximum acuity for this visual task is about 2.

Resolution can be tested with a target having parallel black bars separated

by spaces equal to the width of the bars, similar to targets used for measuring the resolution of photographic systems or components. The maximum acuity for this task is also about 2. Keep in mind that an image can have high resolution yet have poor sharpness and vice versa. Resolution is reported differently for film (lines pairs per inch) than for digital systems. Digital systems use pixels per inch.

Sharpness (acutance) refers to the apparent abruptness of the change in density that occurs at the very edge of an image. (Using an unsharp mask in Photoshop increases sharpness this way.)

Visual acuity can be affected by other factors such as the illumination level, where acuity increases steadily with the illumination level over a wide range. Pupil size also affects acuity, with the maximum being obtained at an opening of approximately *f*/4. At the maximum opening of *f*/2, aberrations lower the acuity, and at the smallest opening of *f*/8 diffraction lowers the acuity.

Motion

Motion refers to a change in position of an object, and the rate of motion is identified as speed. The speed of a moving object may be either too fast to be detected (a speeding bullet) or too slow (the moon, from moonrise to moonset). Slow movement can be detected more easily when the movement takes place in front of stationary objects. One experiment revealed that when a reference grid was removed, the rate of movement of a spot had to be increased 10 times to be detectable. In fact, a stationary spot of light in an otherwise darkened room is commonly perceived as moving—an effect known as the wandering-light phenomenon. Although the speed of a moving object can be measured in units such as miles per hour, viewers in general are not very accurate in estimating the rate of movement. Such ability improves with experience when subjective judgments can be compared to objective measurements—an experienced batter in a baseball game, for example, can detect the difference between an 80 mph pitch and a 90 mph pitch.

The human visual system is designed to detect motion over the entire area of the retina, so that moving objects in the periphery of the field of view, up to 90° to the side, can be detected. If identifying the moving object is important, a semi-reflexive movement of the eyes enables the viewer to position the image of the object on the fovea of the retina, where visual acuity is highest. Once the object is fixated, the visual system is very good in tracking the movement unless the speed is very high and the direction of movement is erratic. Strangely, it is almost impossible to pan the eyes smoothly except when tracking a moving object. Instead, the eyes tend to move in quick jumps, called *saccades*. By closing the eyes, the viewer may be able to pan the eyes smoothly by visualizing tracking a moving object. Skill in tracking rapidly moving objects is important for both motion-picture and still photographers, as well as for participants (and spectators) in many sports and other recreational and occupational activities.

A person can detect movement of an object that is 90 degrees off to one side, but it might be difficult for the person to identify the color of the object.

With current technology, it is impossible to accurately recreate motion photographically. In a single still photograph, it is necessary to rely upon implied motion. A blurred image of a bicycle is generally perceived as representing a rapidly moving object (see Figure 12-18). Similarly, a sharp

Figure 12-18 Blurring the image is one of several methods of representing motion in a still photograph. (Photograph by Natalie Sinisgalli, www.nataliesinisgalliphotography.com.)

The phi phenomenon accounts for the realistic perception of motion when looking at a series of still photographs in a motion picture.

image of a bicycle with a blurred background implies motion. Motion can also be implied without blur, such as a sharp image of a skier going down a steep slope or suspended in air. With two or more still photographs viewed side-by-side, a change in position of an object is perceived as representing movement. A series of such still photographs viewed sequentially in the same position produces a more realistic perception of motion, and if the amount of change in position of the images and the rate of presentation of the still photographs is appropriate the viewer accepts the images as representing smooth and continuous movement, as with contemporary motion pictures.

This perception of motion—when the image of an object appears in different positions in a sequence of still pictures presented in rapid succession—is known as the *phi phenomenon*. The phi phenomenon can be demonstrated in a darkened room with as few as two flashes of light, provided the separation in time and space are appropriate. In sound motion pictures, a projection rate of 24 frames per second produces generally acceptable results, although rapid panning of the motion-picture camera can produce an unrealistic jumpy effect. Early 8-mm motion pictures used a projection rate of 16 frames per second, which was increased to 18 frames per second for super-8 motion pictures.

The phi phenomenon can be demonstrated effectively by illuminating a moving object with a variable-speed stroboscopic light where the flash frequency can be altered from approximately one flash per second to a frequency that produces the perception of a continuous light source (see Figure 12-19). A black circle with a white radial line rotated on a motor will appear to be standing still when the light flashes once per revolution. Slowing down the frequency of the stroboscopic light so that the disk makes a little more than one complete revolution between flashes will make it appear to be rotating in the correct direction. Speeding up the frequency so that the disk does not quite complete a full revolution between flashes will make it appear to be rotating in the reverse direction. This explains why

Figure 12-19 A variable-speed stroboscopic light source was used to record 24 images of a dancer in a single photograph to produce a perception of implied motion. In a sound motion picture, 24 still photographs are projected in rapid sequence to produce a perception of realistic motion because of the phi phenomenon. (Photograph by Andrew Davidhazy.)

wagon wheels sometimes appear to be turning backward in cowboy movies.

Motion-picture photography offers the advantage over direct vision of being able to speed up or slow down motion by altering the rate at which the individual pictures are exposed in the camera. In time-lapse photography, a flower can change from a bud to full bloom in seconds by exposing the film at a rate of about one frame per hour. Conversely, motion that is too rapid to be seen with the eye can be slowed down by using a high-speed motion-picture camera that can expose film at rates up to approximately 10,000 frames per second. If a film exposed at 10,000 frames per second is projected at a rate of 24 frames per second, the rate of movement is reduced to approximately 1/400 the original speed.

Depth

The perception of depth is important to photographers in two different contexts—how depth is perceived when viewing the three-dimensional world, and how depth is perceived when viewing photographs and other two-dimensional representations of the real world. Binocular vision, whereby objects are viewed from slightly different positions with the left and right eyes, is commonly given much of the credit for the perception of depth in everyday life. The fact that a three-dimensional scene does not suddenly appear two-dimensional when we close one eye is evidence that there are other depth cues besides those provided by binocular vision.

Wagon wheels can appear to be turning backwards in motion pictures even though the wagon is moving forward.

When an object in a three-dimensional scene is fixated with both eyes, the images formed in the two eyes are for the most part identical. To the extent that they are identical, the mind can fuse them into a single image. The inability to fuse the two images in certain areas, because of differences in viewpoint of the two eyes, is referred to as *disparity*, and the disparity provides the mind with important depth information (see Figure 12-20).

Disparity can be demonstrated very easily by looking at a fairly close object, then covering the left and right eyes alternately and noting how objects in the background seem to change position. If the background jumps when the right eye is covered but not when the left eye is covered, the indication is that the right eye is the dominant eye. Photographers usually feel more comfortable when they use the dominant eye for operations that can be done with only one eye, such as using a camera viewfinder or a focusing magnifier.

Three-dimensional scenes do not suddenly appear flat when one eye is closed.

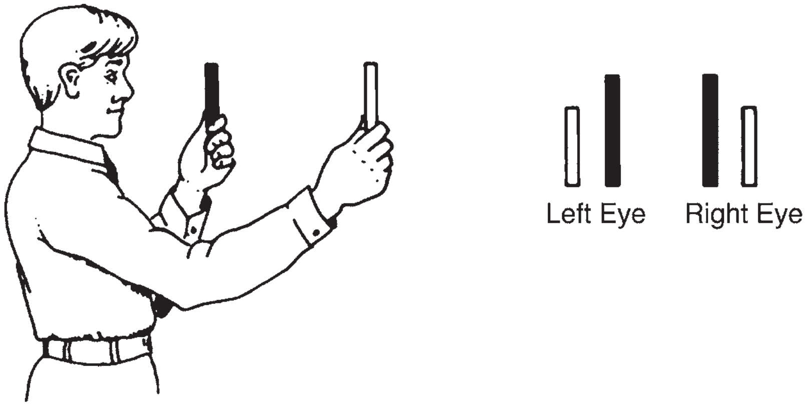


Figure 12-20 Binocular disparity.

Photographers tend to use their dominant eye when looking through a viewfinder.

Disparity becomes so slight with objects at distances greater than approximately 450 feet that binocular vision contributes little to depth perception. Since the pupils in the eyes are separated, on the average, by 2.5 inches, at a distance of 450 feet the ratio of distance to separation is approximately 2000:1. Conversely, at very close distances the disparity increases, and it is even possible to see opposite sides of one's hand when it is placed in a thumbing-the-nose position. When completely different images are presented to the two eyes with an optical device, so that no fusion is possible, the mind tends to reject one image or the other, sometimes both on an alternating basis.

There is no disparity when a person looks at a photograph or other two-dimensional image with both eyes. Thus, the perception of depth in photographs must be due to cues other than binocular vision. On the other hand, the absence of disparity in two-dimensional pictures may remove a minor source of tension that makes some realistic pictures more satisfying to look at than the original scenes they represent.

Stereopsis, the perception of depth due to binocular vision, can be created in photographs. By taking two photographs of the same scene from slightly different positions, separated horizontally by about 2.5 inches, and presenting them so that each eye sees only the photograph taken from the corresponding position, the same disparities are produced as when looking at the original scene. Various methods have been used to present the two images to the appropriate eyes. With the stereoscope, the pictures are placed side by side and the lenses make it possible for each eye to view the corresponding image. Viewing specially colored superimposed images with glasses that have different-color filters or polarizing filters that are rotated at right angles to each other can eliminate the need for stereoscope lenses. The two images can also be presented as alternating narrow strips covered with transparent lenticular embossings that present each set of strips to the appropriate eye. With holography, there is a single photographic image, but different interference patterns are presented to the two eyes so that the reconstructions constitute different images.

Convergence of the two eyes is stronger when viewing a close-up object than a distant object, thereby providing the mind with additional binocular information about depth (see Figure 12-21). Also, the focus of the eyes changes with object distance, although this is not a binocular function and the viewer is usually aware of the effect only when the object distance approaches the near point—the shortest distance the eye can focus on without strain. The near point varies among individuals, and increases with age from a minimum of approximately 3 inches to a maximum of approximately 84 inches.

Although the eyes have a limited depth of field, like photographic lenses, the depth of field of the eyes tends to be relatively large because

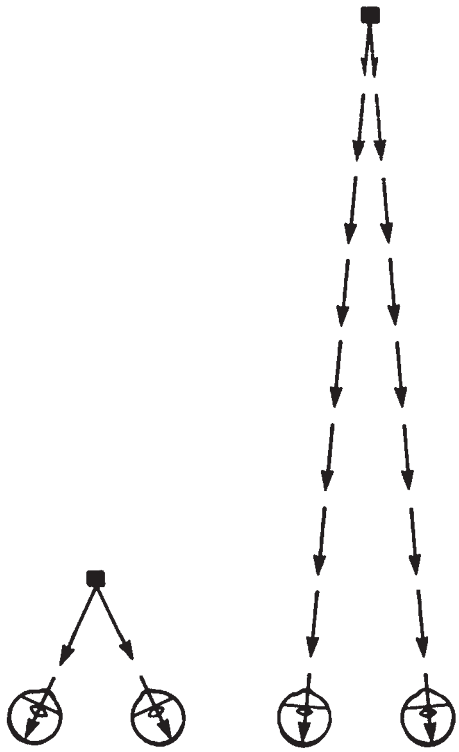


Figure 12-21 Convergence.

of the short focal length (17 mm). In addition, since the focus changes automatically as we look at different parts of a three-dimensional scene, and the angle of critical vision is very narrow, depth of field plays a much smaller role in the perception of depth in the real world than it does in photographs.

Perspective

Remembering that perspective refers to the appearance of depth when a three-dimensional scene is represented in a two-dimensional image such as a photograph or drawing, or when a scene is viewed directly. Photographers have a number of additional cues or methods that create the appearance of depth in photographs, including the following:

Depth of Field. Use of a limited depth of field, so that the objects in front of and behind the point of focus in the image are unsharp, creates a stronger appearance of depth or perspective than when the entire scene appears sharp.

Lighting. Depth can be emphasized with lighting that produces a gradation of tones on curved surfaces, that produces a separation of tones between the planes of box-shaped objects and between objects and backgrounds, and that casts shadows of objects on the foreground or background.

Overlap. Arranging a scene so that a nearby object obscures part of a distant object provides the viewer with powerful clues as to the relative distances of the objects.

Aerial Haze. The scattering of light that occurs in the atmosphere makes distant objects appear lighter and less contrasty than nearby objects. Thick fog and smoke can create the illusion of depth with relatively small differences in distance.

Color. Red is referred to as an advancing color and blue as a receding color. In the absence of conflicting depth clues, a blue surface tends to appear farther away than a red surface at the same distance.

Stereophotography. Viewing two photographs taken from slightly different positions so that the left eye sees one and the right eye sees the other produces a realistic effect with strong depth clues similar to those produced with binocular vision and three-dimensional objects.

Holography. With a single photographic image, holograms present different images to the left and right eyes, as with stereo pairs, but they also produce motion parallax for objects at different distances when the viewer moves laterally.

Linear Perspective. Linear perspective is exemplified by the convergence of parallel subject lines, and the

The perceived size of an object has little relationship to the size of the image on the retina.

Photographers have many different ways of representing three-dimensional depth in two-dimensional photographs.

Image size is directly proportional to focal length and is inversely proportional to object distance.

Moving a camera farther away from a subject weakens the linear perspective.

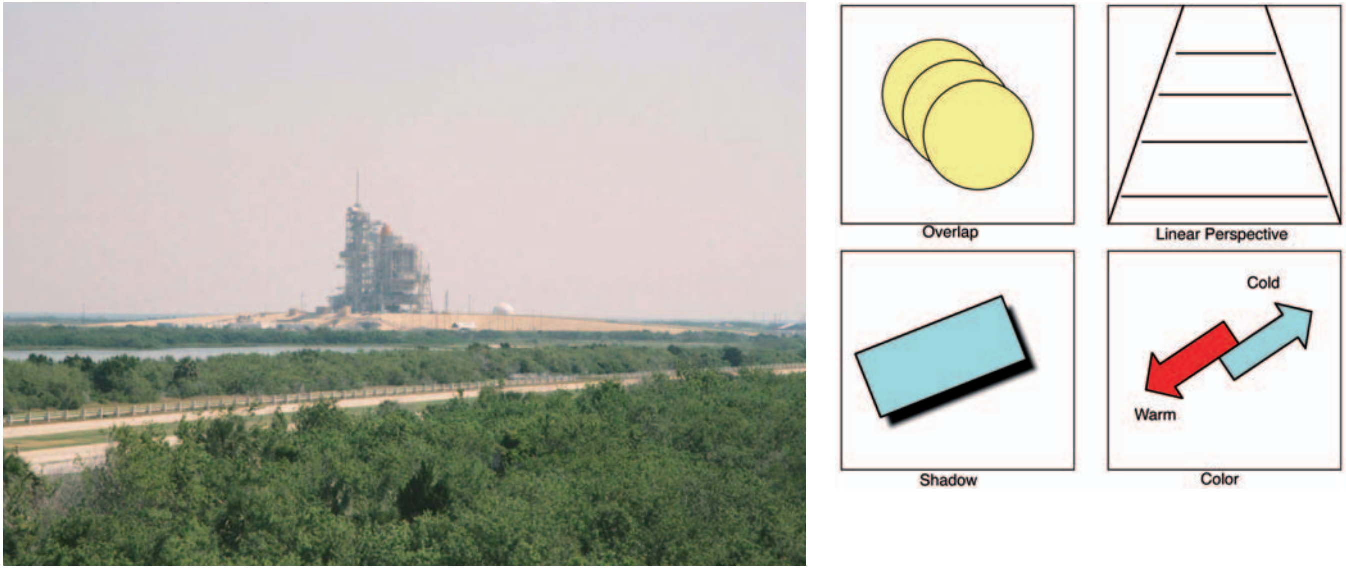


Figure 12-22 Some depth cues include haze, overlap, linear perspective, shadow, and color.

Figure 12-23 Three-dimensional form in the original scene is represented by the different planes of the ceiling, wall, and floor; the bench; and even the protruding bricks that make up the triangular designs in the wall. The pattern of the protruding bricks is reduced in size sufficiently so that the viewer can visualize feeling the roughness of the pattern with the fingertips, a characteristic of texture. (Photograph by James Craven.)

decrease in image size as the object distance increases. Linear perspective is so effective in representing depth in two-dimensional images that it is often the only type of depth clue provided by artists when making simple line drawings. Figure 12-22 provides examples of some of the above methods.

So far, the emphasis in the discussion of depth has been on the perception of distance, but the term *depth* properly includes two other important categories—form and texture. Form refers to the three-dimensional quality of objects, as distinct from the two-dimensional outline shape (see Figure 12-23). Form is the quality that can be determined through the sense of touch with the eyes closed, such as the spherical form of a baseball or the cubical form of a pair of dice. Effective representation of form in two-dimensional photographs depends largely upon the choice of an appropriate viewpoint and the use of light to reveal the different planes and curved surfaces with highlights, shadows, and appropriate gradations of tone.

Texture refers to the small-scale depth characteristics of a type that might be felt with the fingertips, such as the roughness of a wood file or the smoothness of window glass. Effectively representating texture in two-dimensional photographs depends largely upon using an appropriate scale of reproduction, as well as lighting that produces shadows in the recessed areas and highlights in the

raised areas. Photographs made through optical and electron microscopes reveal that many surfaces thought of as being smooth, such as writing paper, appear to have a rough texture or even form and distance when magnified sufficiently. Conversely, the mountains on the moon appear to have a finger-touching type of texture when photographed from a distance with a small scale of reproduction.

Linear Perspective

Now that we have discussed many of the aspects of perception, let's explore how we can control perspective in photography. In photographs, changes in linear perspective are commonly associated with changes in camera position and the focal length of camera lenses. If the definition of linear perspective were limited to the relative image size of objects at different distances (or the angle of convergence of parallel subject lines) the photographer's control would be limited to the choice of camera position (that is, object distance). If changes in the appearance of linear perspective were included even when there is no change in the relative image sizes of objects at different distances, then lens focal length would have to be included as a control.

Two basic assumptions important to an understanding of the control of linear perspective are the following:

1. *Image size is directly proportional to focal length*.
2. *Image size is inversely proportional to object distance*.

Object Distance and Image Size

Placing two objects of equal size at distances of 1 foot and 2 feet from a camera lens produces images that vary in size in a 2:1 ratio. Recalling that image size is inversely proportional to object distance, the smaller of the two images corresponds to the object at the larger distance. Actual image sizes could be determined given the object size, focal length, and object distances with either graphical drawings or lens formulas as discussed in the Optics chapter, but for now we will be concerned only with relative image sizes.

Linear perspective is based on the ratio of image sizes for objects at different distances. Figure 12-24 shows two objects of equal size at distance ratios of 1:2, 1:3, and 1:4. The sizes of the resulting images are in ratios of 2:1, 3:1, and 4:1. Thus, with movable objects the relative image sizes and linear perspective can be controlled easily by changing the positions of the objects. Most of the time, however, we photograph objects that cannot

Strong perspective makes a room appear larger in a photograph, but it is inappropriate for a formal portrait of a person.

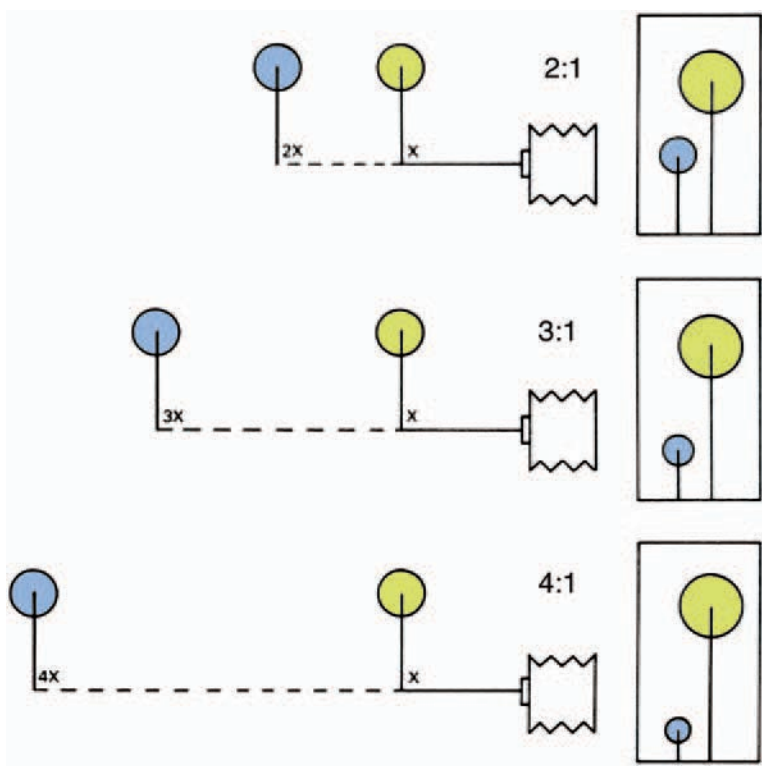


Figure 12-24 Image size is inversely proportional to object distance. The ratios of the object distances from top to bottom are 2:1, 3:1, and 4:1.

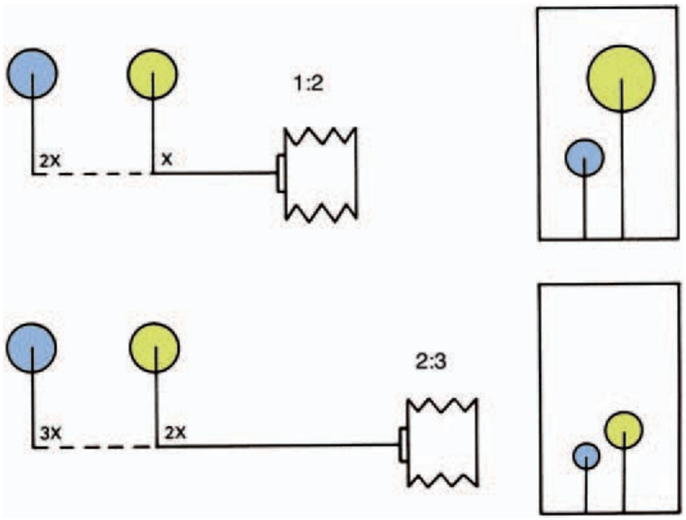


Figure 12-25 Doubling the distance from the camera to the near object changes the ratio of distances to the two objects from 1:2 to 2:3.

Figure 12-26 Space appears to be compressed in the bottom photograph, made with a 150-mm lens, compared to the top photograph, made with an 18-mm lens from a closer position.

be moved easily, and therefore the options available to control perspective or alter image size are either moving the camera or changing the focal length of the lens.

Let's start with two objects that are at a distance ratio of 1:2 from the camera. Next we will move the camera away to double the distance from the closer object. Doing this does not double the distance to the farther object. Therefore, the ratio of the image sizes will not remain the same. The ratio of object distances changes from 1:2 to 2:3 by moving the camera, the ratio of image sizes changes from 2:1 to 3:2 (or 1.5:1) (see Figure 12-25). Moving the camera farther away from the subjects reduces the size of both images and also makes them appear nearly equal in size. The two images will never be equal in size, no matter how far the camera is moved away, but with very large object distances the differences in size can become insignificant.

The linear perspective produced by moving the camera farther from the objects is referred to as a *weaker perspective* than that produced with the camera in the original position. Thus, weak perspective is an attribute in a picture in which image size decreases more slowly with increasing object distance than expected. Another aspect of weak perspective is that space appears to be compressed, as though there were less distance between nearer and farther objects than actually exists (see Figure 12-26).

Conversely, moving a camera closer to the two objects increases the image size of the nearer object more rapidly than that of the farther object, producing a *stronger perspective*. For example, with objects at a distance ratio of 1:2, moving the camera in to one-half the original distance to the near object doubles its image size

but reduces the distance to the farther object from 2 to 1.5, therefore increasing the image size of the farther object to only 1 1/3 times its original size. Strong perspective is especially flattering to architectural photographs of small rooms because it makes the rooms appear more spacious.

A word of caution about the assumption that image size varies inversely with object distance. This relationship holds as long as the lens-to-image plane distance remains the same for the two objects. It will not hold when the back of a view camera is swung or tilted. Indeed, one purpose of these adjustments is to control the shape of the image. Neither will the relationship hold when separate photographs are made of each of the two objects and the camera is focused in turn on each object distance, which changes the lens-to-image plane distance. This is significant mostly with close-up photography. For example, with objects at distances of 8 inches and 16 inches from a camera equipped with a 4-inch focal length lens, the ratio of image sizes is 2:1 when the objects are photographed together but 3:1 when they are photographed separately and the camera is refocused. To solve this problem for other object distances, use the lens formula $R = f/(u - f)$.

Focal Length and Image Size

Serious photographers have more than one focal-length lens per camera in order to control image size and the corresponding angle of view. As stated above, image size is directly proportional to focal length. Thus, if an image of a building is 1/2 inch high in a photograph made with a 50-mm focal length lens on a 35-mm camera, substituting a 100-mm focal length lens will produce an image of the building that is 1 inch high. Since this is a direct relationship, doubling the focal length will double the image size. Also, since doubling the focal length will double the size of all parts of the image, it will not change the ratio of image sizes for objects at different distances (see Figure 12-27). This can be demonstrated convincingly with a camera equipped with a zoom or variable focal length lens. As the focal

Figure 12-27 Photographs made from approximately the same position with 400-mm (left), 200-mm (middle), and 100-mm (right) focal length lenses. Image size changes in proportion to focal length, but relative sizes for objects at different distances remain constant. (Images by Trevor Clement and Robert Weber.)

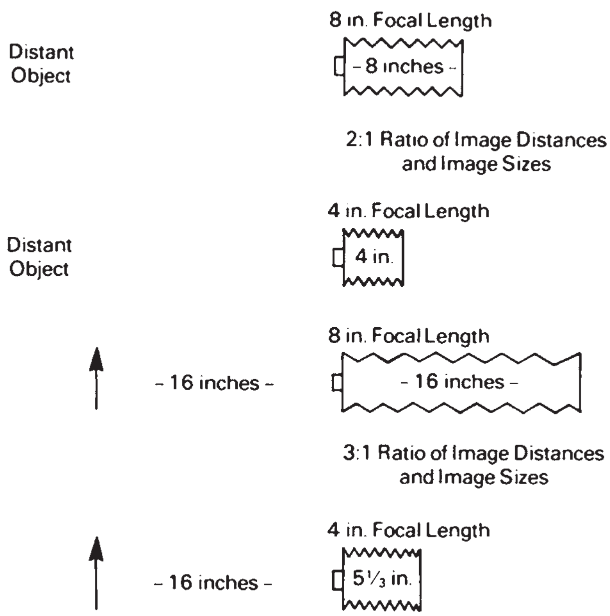


Figure 12-28 Image size is proportional to lens focal length with distant objects (top). With small object distances the ratio of the image sizes is larger than the ratio of the focal lengths (bottom).

length is changed, one can see the overall image change in size, but the relative sizes of images of objects at different distances remain the same. (Although the relative sizes remain the same, the linear perspective may appear to change, a phenomenon we will examine in the section on viewing distance.)

The camera-to-subject distance, not focal length of the lens, determines linear perspective.

There is an exception to the assumption that image size is directly proportional to focal length. The assumption holds when the image distance is approximately equal to the focal length—that is, when photographing objects at moderate to large distances. When photographing objects at close distances, the lens-to-film distance must be increased to focus the image, and the size relationship with different focal-length lenses deviates from that predicted by the assumption. For example, with an object at a distance of 16 inches from a camera equipped first with an 8-inch focal length lens and then with a 4-inch focal length lens, the ratio of image sizes will be 3:1, rather than the expected 2:1. The same lens formula $R = f/(u - f)$ is used to solve this problem (see Figure 12-28).

Changing the viewing distance of a photograph can make the perspective appear stronger or weaker.

Changing Object Distance and Focal Length

Photographers commonly change focal length and object distance simultaneously to control linear perspective and overall image size. For example, if the perspective appeared too strong and unflattering in a portrait made with a normal focal-length lens, the photographer would substitute a longer focal-length lens and move the camera farther from the subject to obtain about the same size image but one with weaker perspective. Because short focal length wide-angle lenses tend to be used with the camera placed close to the subject, and long focal-length telephoto lenses tend to be used with the camera at relatively large distances, strong perspective is often associated with wide-angle lenses and weak perspective is similarly associated with telephoto lenses, although it is the camera position and not the focal length or type of lens that produces the abnormal linear perspective.

The change in linear perspective with a change in object distance is seen most vividly when a corresponding change is made in the focal length to keep an important part of the scene the same size. In Figure 12-29, for example, the focal length of the lenses and the camera positions were adjusted to keep the images of the nearer object the same size, and the difference in linear perspective is revealed by the difference in size of the images of the farther object.

Figure 12-29 Photographs made with a 200-mm focal length lens (left) and a 100-mm focal length lens (right) with the camera moved closer to match the image size of the foreground object. The change in the relative sizes of the two objects is due to the change in the camera position.

In situations in which a certain linear perspective contributes significantly to the photograph's effectiveness, the correct procedure is first to select the camera position that produces the desired perspective, and then to select the focal length lens that produces the desired image size. For example, if the photographer wants to frame a building with a tree branch in the foreground, the camera must be placed in the position that produces the desired size and position relationships between the branch and the building. The lens is then selected that forms an image of an appropriate size. A zoom lens offers the advantage of providing any focal length between the limits. With fixed focal-length lenses, if the desired focal length is not available, and changing the camera position would reduce the effectiveness because of the change in perspective, the best procedure is to use the next shorter focal-length lens available and then enlarge and crop the image.

Cameras cannot always be placed at the desired distance to achieve the linear perspective wanted. Whenever photographs are made indoors, there are physical limitations on how far away the camera can be placed from the subject because of obstacles, such as walls. Fortunately, the strong perspective that results from using short focal length wide-angle lenses at the necessarily close camera positions enhances rather than detracts from the appearance of many architectural and other subjects. There are also many situations in which the camera must be placed at a greater distance from the subject than would be desired. For example, cameras often cannot be located close to sporting activities as they may interfere with the athletes, block the view of spectators, or endanger the photographer.

The correct viewing distance of a photograph for a normal-appearing perspective is equal to the camera lens focal length multiplied by the negative-to-print magnification.

Not all subjects will experience a change in perspective with a change of object distance. For example, a two-dimensional object has no depth. Photographs of such an object will not reveal a change in the relative size of different parts of the image with changes in camera distance. Therefore, photographic copies of paintings, photographs, printed matter, etc., made from a close position with a short focal length wide-angle lens, and from a distant position with a long focal length telephoto lens, should be identical.

Viewing Distance

It would seem that the distance at which we view photographs should have no effect on linear perspective, because an image size ratio of 2:1 of objects at different distances will not be altered by changes in the viewing distance. In practice, however, changes in viewing distance can significantly affect the perspective, provided the photographs contain good depth clues. Photographs of two-dimensional objects appear to change little with respect to linear perspective when viewing distance is changed, whereas those containing dominant objects in the foreground and background or receding parallel lines can change dramatically.

We seldom experience unnatural-appearing linear perspective in real life. Abnormally strong or weak perspective tends to occur only when we look at photographs or other two-dimensional representations of three-dimensional objects or scenes such as on a television or computer screen. The reason perspective appears normal when we view a three-dimensional scene directly is that as we change the viewing distance, the perspective and the image size change simultaneously in an appropriate manner. We also normally know whether we are close or far away from the scene we are viewing, so the corresponding large or small differences in apparent size of objects at different distances seem normal for the viewing distance. (It is possible to deceive viewers about the size or shape of objects or their distances, but we will discuss such illusions later.)

To illustrate how the situation changes when we view photographs rather than actual three-dimensional scenes, assume that two photographs are made of the same scene, one with a normal focal length lens and the other with a short focal length lens with the camera moved closer to match the image size of a foreground object (see Figure 12-29). Looking at the two photographs, viewers suppose that they are at the same distance from the two scenes because the foreground objects are the same size, but if the perspective appears normal in the first photograph, the stronger perspective in the second photograph will appear abnormal for what is assumed to be the same object distance. Viewers can make the perspective appear normal in the second photograph, however, by reducing the viewing distance. The so-called "correct" viewing distance is equal to the focal length of the camera lens (or, more precisely, the image distance) for contact prints, or the focal length multiplied by the magnification for enlarged prints.

The correct viewing distance for a contact print of an 8 × 10-inch negative exposed with a 12-inch focal length lens is 12 inches. Observers tend to view photographs from a distance about equal to the diagonal causing the perspective to appear normal to most viewers. If the 12-inch lens were replaced with a 6-inch focal-length lens, the print would have to be viewed from a distance of 6 inches

for the perspective to appear normal. When the print is viewed from a comfortable distance of 12 inches, the perspective will appear too strong. Conversely, the perspective in a photograph made with a 24-inch focal length lens would appear too weak when viewed from a distance of 12 inches. It is fortunate that people tend to view photographs from standardized distances rather than adjusting the viewing distance to make the perspective appear normal, for that would deprive photographers of one of their most useful techniques for making dramatic and effective photographs.

The Wide-Angle Effect

Closely related to the way a change in viewing distance can change the perspective of photographs is the influence of viewing distance on the so-called wide-angle effect. The wide-angle effect is characterized by what appears to be distorted image shapes for three-dimensional objects near the corners of photographs. This effect is especially noticeable in group portraits, where heads appear to be stretched out of shape in directions radiating away from the lens axis or the center of the photograph. Thus, heads near the sides seem to be too wide, those near the top and bottom seem to be too long, and those near the corners appear to be stretched diagonally (see Figure 12-30).

This stretching occurs because rays of light from off-axis objects strike the image plane at oblique angles rather than at a right angle, as occurs at the lens axis. If the subject consists of balls or other spherical objects, the amount of stretching can be calculated in relation to the angle formed by the light rays that form the image and the lens axis. Thus, at an off-axis angle of 250 the image is stretched about 10%, and at 45° the image is stretched about 42%. (The image size of off-axis objects changes in proportion to the secant of the angle formed by the central image-forming ray of light with the lens axis. The reciprocal of the cosine of the angle may be substituted for the secant.) Normal focal length lenses, where the focal length is about equal to the diagonal of the film, have an angle of view of approximately 50°, or a half angle of 25°.

Figure 12-30 The image of a spherical light globe in this cropped section of photograph taken with a short focal length lens is stretches approximately 60% in a direction away from the lens axis.

The wide-angle effect refers to elongated images of objects near the edges of photographs made with short focal-length wide-angle lenses.

Why don't we notice the 10% stretching that occurs with normal focal length lenses? It is not because a 10% change in the shape of a circle is too small to be noticed, but rather that when the photograph is placed at the correct viewing distance, the eye is looking at the images at the edges at the same off-axis angle as the angle of the light rays that formed the image in the camera. Thus, the elliptical image of the spherical object is seen as a circle when the ellipse is viewed

obliquely. The effect would be the same even with the more extreme stretching produced with short focal length wide-angle lenses if the photographs were viewed at the so-called correct viewing distance. Since the correct viewing distance is uncomfortably close for photographs made with short focal length lenses, people tend to view them from too great a distance, where the stretching is apparent.

One might question why the wide-angle effect does not occur when photographing circles drawn on paper as it does when photographing three-dimensional objects. The distinction is that if one looks at a row of balls from the position of the camera lens, the outline shape of all of the balls will appear circular, whether they are on or off axis, but off-axis circles drawn on paper will appear elliptical in shape because they are viewed obliquely. The compression that produces the ellipse when the circle is viewed from the lens is exactly compensated for by stretching when the image is formed because the light falls on the image plane at the same oblique angle at which it leaves the drawing (see Figure 12-31).

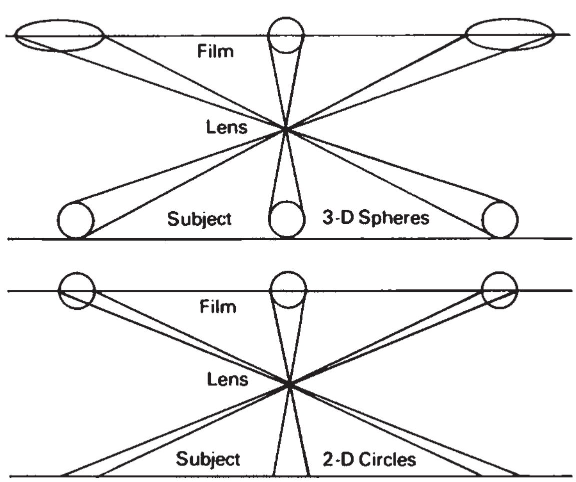


Figure 12-31 The wide-angle effect results in elongation of off-axis images of three-dimensional objects (top). Images of two-dimensional objects such as circles in a painting or photograph are not affected (bottom).

REVIEW QUESTIONS

1. Persistent images last . . .
   A. approximately 1/100 second
   B. approximately 1/4 second
   C. approximately 5 seconds
   D. as long as the viewers concentrate on the images
2. With respect to the perception of realism when viewing motion pictures, persistent images . . .
   A. contribute to the perception
   B. interfere with the perception
   C. have no effect on the perception
3. If a slight amount of flicker is apparent when viewing a motion picture, reducing the projector-to-screen distance to obtain a smaller and brighter image will . . .
   A. decrease the flicker
   B. increase the flicker
   C. have no effect on the flicker
4. The “spots” one sees after looking directly at a flash tube when it is fired are properly identified as . . .
   A. persistent images
   B. afterimages
   C. aftereffects
   D. eidetic images
   E. memories
5. To recall a visual image from a motion picture viewed an hour earlier would be identified as . . .
   A. an afterimage
   B. a short-term memory image
   C. a long-term memory image
   D. a rerun
6. The difference between the red and the blue in the U.S. flag is primarily in . . .
   A. saturation
   B. hue
   C. value
   D. chroma
   E. lightness
7. Persons having normal color vision are identified as normal . . .
   A. monochromats
   B. dichromats
   C. trichromats
   D. stereomats

8. The percent of Caucasian [EO8]males who have defective color vision is approximately . . .

   A. 0.4
   B. 2
   C. 4
   D. 8
   E. 16

9. The maximum response range of the visual system to luminance variations is approximately . . .

   A. 100 to 1
   B. 10,000 to 1
   C. 1 million to 1
   D. 10 trillion to 1

10. The perceptual phenomenon of seeing yellow on a television screen in an area of red and green pixels is identified as . . .

    A. simultaneous contrast
    B. successive contrast
    C. local adaptation
    D. Assimilation

11. The fact that the image of a tilted circle in a photograph is generally perceived as a tilted circle rather than its actual elliptical shape is attributed to . . .

    A. shape constancy
    B. shape generalization
    C. sharpening
    D. leveling
    E. closure

12. Binocular vision contributes most strongly to the perception of depth when viewing . . .

    A. photographs close up
    B. photographs at a distance
    C. three-dimensional objects close up
    D. three-dimensional objects at a distance

13. The moon tends to appear larger when it is near the horizon than when it is overhead because of . . .

    A. differences in refraction of light by the atmosphere
    B. differences in perceived distances of the moon
    C. size constancy
    D. size adaptation

14. The perception of motion when viewing a series of still photographs in a motion picture in rapid succession is identified as . . .

    A. a persistent image
    B. the gamma effect
    C. fusion
    D. motion adaptation
    E. the phi phenomenon

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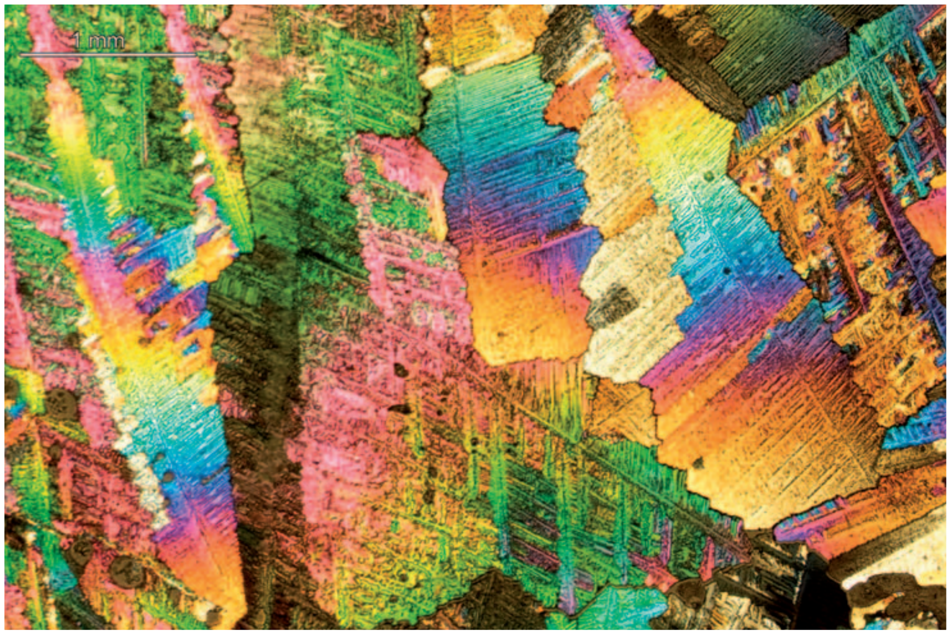
chapter 13

Chemistry for Photographers



Photograph by Jessica Peterson, Biomedical Photographic Communication student, Rochester Institute of Technology.

Edited by Paul A. Schwartz

Introduction

Photographers today have many choices regarding the materials and technologies available to them for exposing, processing, and printing images. In each of these steps, chemical substances play a key role in defining both the characteristics and quality of the images generated. At the time the camera shutter opens, light energy is focused on the image plane where a sensor is positioned. Digital cameras rely on an image sensor, a microelectronic semiconductor device, which converts the image to an electronic signal and begins the series of conversions known as image processing. The image data is sent to magnetic storage such as a flash card or other portable media. Film camera systems use silver halide films that capture latent image that will be amplified and stabilized via chemical processes. The final image is retained in the film.

Image Capture

Currently three main types of digital image sensors are available.

Charge Coupled Device (CCD)—A specialized semiconductor material that produces high-quality images. It was invented at Bell Labs in the late 1960s. Like almost all semiconductors, they are produced from doped-silicon wafers. Functionally,

light is converted to charge; photons to electrons.

Complementary Metal Oxide Semiconductor (CMOS)—A standard semiconductor material that has been developed into image sensors. These sensors generally require less power than CCD and have found application in scanners, cell phone cameras, and digital and video camera systems. CMOS sensors have also reduced the costs of digital imaging as they are able to be fabricated with lower cost.

Foveon Sensors—A structured CMOS imaging semiconductor designed using three distinct layers which aims to improve light sensitivity and color reproduction. Foveon sensors were announced in the 2002.

In film camera systems, silver halide salts represent a category of chemical substances which have high reactivity to light in the visible and ultraviolet regions of the electromagnetic spectrum. Photographic films have allowed for many types of photographic innovations to occur. The fundamental reaction of silver halide photographic materials is the reaction of light to form latent image; photons to silver specks.

$$AgX + h\nu \rightarrow Ag^{*} + X\text{-}$$

Silver halide salts serve as the image sensor. Film speed is defined by the sensitivity of these silver halide grains to light energy. Commonly, in the preparation film emulsions, an intentional doping of trace metal can improve the light sensitivity of the silver halide crystals. These dopants are often referenced as chemical sensitizers. Gold salts and certain rhodium and iridium complexes are among the materials used for chemical sensitization of silver halide film emulsions.

Silver catalyzed dye formation in structured color films and color papers is another image capture method which has benefits in many photographic applications. The color film and paper structures have been optimized to produce accurate color reproduction and other image quality characteristics, such as sharpness and grain have also been co-optimized.

Image storage onto magnetic media such as hard drives and flash storage is common for photographic image storage and data storage of other information. The materials and devices for data storage are continually improving in both convenience and reliability. Optical storage media such as CD or DVD are also convenient data storage and backup materials. The organic dyes in these media, define how permanent the data written onto these materials will be. The capacity and density of the data is defined by the storage media. Image retrieval and image stability are additional factors to be considered in setting a method for storing images both for near-term use and for archiving images.

Image Display

Final image presentation on paper, dye or ink on paper is also connected to the chemicals used in the process. Currently, the three main methods of printing images to paper in photographic systems are:

Inkjet printing, which uses a set of cyan, magenta, yellow, and black dyes or pigments to print onto coated paper for image display.

Chromogenic dye formation from silver halide photographic prints is a well-established method of forming image onto paper.

Thermal dye transfer methods produce dye onto paper prints.

Also, silver, platinum, palladium, cyanotype, and other variations of early photographic technologies continue to interest printmakers for their proven longevity and unique image tones.

Basic Chemistry

In order to understand photographic chemistry, we must review the basic concepts of general chemistry. The universe consists of a number of elements. Ninety-two of these occur naturally, but elements heavier than uranium have been created by means of nuclear bombardment and radioactive decay. These elements have distinct characteristics and can be divided into two groups—metals and nonmetals. Each element is composed of atoms, which are the practical minimum particle that has the characteristics of an element. Atoms consist of the subatomic particles of protons, neutrons, and electrons. Electrons are generated in many photochemical reactions which produce latent images in silver halide systems and, more directly, voltage in digital imaging sensors. Physicists have broken atoms into still smaller subatomic particles, but it is not necessary to go deeply into this to understand photographic chemistry.

The periodic table is a logical arrangement of the elements according to their chemical and physical properties.

The Periodic Table

In 1869, Mendeleev arranged the then-known atoms into a table, according to their chemical and physical properties. At first there were 89 elements in the table. A few years ago this number was extended to 103. The standard table as of October 2006 has 117 elements. Figure 13-1 has 118 elements present, but element 118, ununoctium, has been discovered. The name ununoctium,

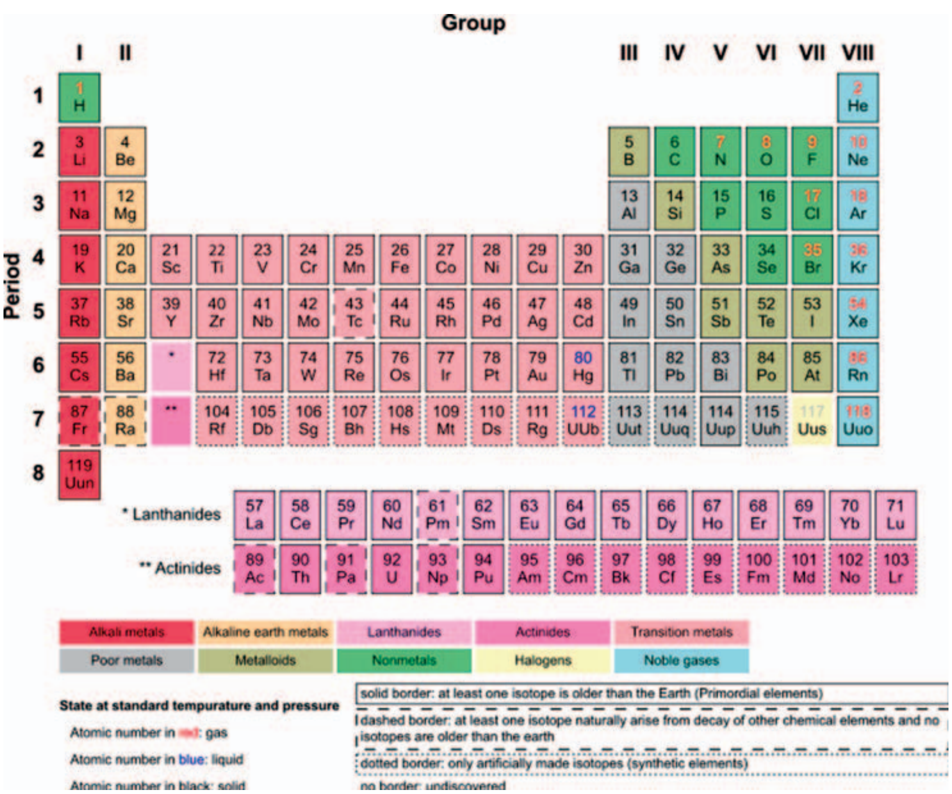


Figure 13-1 One form of the periodic table in which the atoms are arranged according to their chemical and physical properties. As the atomic numbers increase, so do the atomic weights.

which is a systematic element name, is being used until the International Union of Pure and Applied Chemistry (IUPAC) can determine a permanent name for this element. When more recent information concerning the atomic structure became available, it gave further support to the arrangement of the table. The atomic number is equal to the positive charge of the nucleus in the atom, that is, the number of protons in the nucleus. The first column of the table contains the *alkali metals*—lithium, sodium, potassium, rubidium, cesium, and francium. Near the other side of the table can be found the *halogens*—fluorine, chlorine, bromine, iodine, and astatine. Other groups of elements are similarly grouped in the table.

Atoms are the smallest bits of elements that can combine chemically.

Atoms

The smallest atom is that of hydrogen, which consists of a single positive nucleus surrounded by one electron. All of the other atoms have a nucleus of higher positive charge, with corresponding electrons orbiting around the nucleus, and which have a total negative charge equal to the positive charge of the nucleus. Thus a stable atom is neutral. The atomic number is the number by which the charge on the hydrogen nucleus must be multiplied to equal the nuclear charge of the atom. These numbers determine the chemical behavior of the elements, and also support the arrangement of the atomic table (see Figure 13-2).

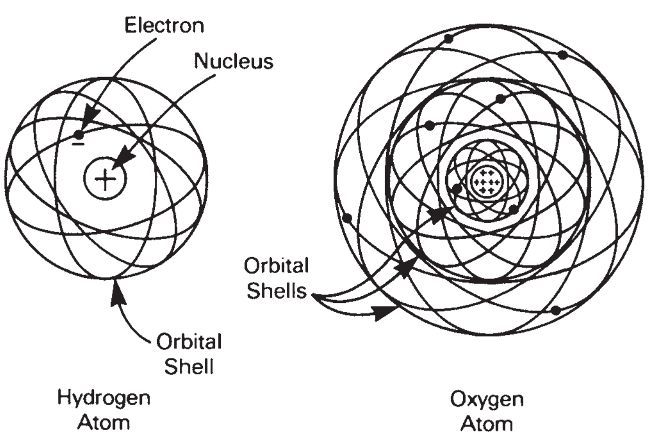


Figure 13-2 The hydrogren atom has 1 electron in orbit around a nucleus with a single positive charge. The oxygen atom has 8 electrons orbiting in shells around its nucleus, with an equal number of positive charges.

The various elements are designated by their symbols; that is, the symbol for hydrogen is H, He for helium, Na for sodium (for *natrium*, its Latin name), K for potassium (*kalium*). The element names and symbols are defined in the periodic table. When two or more atoms are combined, such as O_2 and O_3 to become molecules of oxygen and ozone, each molecule of O_2 contains two atoms of oxygen. Each molecule of ozone O_3 contains three atoms of oxygen. Most molecules are made of different atoms and they are called *chemical compounds*. Potassium bromide is a compound commonly used in photography.

Many compounds are made up of more than two elements, in which case two or more of each of the elements assume the charge characteristic of a single element. For example, ammonium chloride (NH_4Cl) in solution ionizes into NH_4^+ and Cl^-. The NH_4^+ is a positively charged ion, a cation.

Atoms are neutral—the balance of electrons orbiting the nucleus has a negative charge equal to the positive charge of the nucleus. Compounds formed from a metal and a non-metal are defined as ionic compounds. They will dissociate into separate atoms, each having a positive or negative electronic charge. Sodium chloride (NaCl), for example, when heated to make it molten, forms sodium ions (Na^+) and chlorine ions (Cl^-); also a solution of sodium chloride in water, dissociates into ions.

Chemical compounds have different physical characteristics from those of the atoms that are combined to make the compounds. Such properties as melting points, solubility in water or other solvents, crystalline form and color, and specific gravity or density are some of the characteristics that differentiate various compounds. *Inorganic compounds* are those containing metals, and do not contain the element carbon, with the exception of the oxides of carbon compounds containing the carbonate (CO_3^{2-}) ion. *Organic compounds* are those containing carbon with the exceptions noted above usually along with hydrogen, oxygen, sulfur, nitrogen, iodine, phosphorous, and other elements. The *benzene ring*, a ring of 6 carbon atoms with hydrogen atoms attached, is the basis for most photographic developing agents and colored dyes and pigments. Organic compounds are often not very soluble in water, and they are combined with sodium or similar alkali to form a salt that is more soluble in aqueous solutions, with the compound retaining most of its desirable photographic characteristics.

Valence

Depending on the number of electrons in their outer orbitals, elements combine to form compounds in various whole-number proportions. Thus a sodium atom with a valence of one electron will readily form sodium ion (Na^+) and a chlorine atom with a valence of seven electrons will readily form chloride ion (Cl^-) and they can combine to form NaCl, sodium chloride. Gold, with a valence of one or three, takes a valence of three (Au^{+++}) and each atom requires three chlorine atoms to form gold chloride ($AuCl_3$). Nitrogen can have a valence of three or five. Oxygen has a valence of two, so two atoms of nitrogen can unite with three atoms of oxygen to form N_2O_3 (nitrous anhydride). When nitrous anhydride combines with a molecule of water (H_2O), it forms two molecules of nitrous acid ($2HNO_2$).

Atomic Weight

The *atomic weight* is the relative weight of the atom or very near to the weight of the nucleus (protons + neutrons) of the atom. For example, the atomic weight of oxygen is 16. The *molecular weight* of a compound is the total of the weights of the atoms making up the molecule. To form a given quantity of a compound without any of the atomic or molecular components left over, the reaction is carried out with amounts that are proportional to their atomic or molecular weights. When 23 grams of sodium (atomic weight—23) are combined with 35.5 grams of chlorine (atomic weight—35.5), 58.5 grams of sodium chloride (molecular weight—58.5) are formed. A molar solution is one that has the same number of grams as the molecular weight dissolved in one liter of water. Such solutions would have equal numbers of molecules of chemicals dissolved in them, and equal numbers are then available for reaction. A 1 molar solution of sodium chloride would contain 58.5 grams per liter.

Chemical Reactions

When chemical compounds are mixed, and the conditions favor forming new compounds a chemical reaction takes place; reactants form products. If a chemical reaction occurs in a liquid solution the compounds may remain in solution, or they may precipitate as a solid out of the solution. If a product

The *benzene ring,* a ring of 6 carbon atoms with hydrogen atoms attached, is the basis for most developing agents.

Ions are atoms that have a positive or negative charge.

Atoms can combine to form compounds. The number of each type of atom required depends on its valence.

Atomic weights are the relative weights of atoms with the weight of oxygen taken as 16.

A molar solution is one that has the same number of grams as the molecular weight dissolved in one liter of water.

When oxidation occurs, reduction also occurs.

of the reaction is a gas, it is given off and removed from the reaction. In either case, the reaction proceeds in the direction of the compound that is being removed, until the quantity that can remain in solution under the conditions is reached. If the reaction products, precipitate or gas, are removed, the reaction can continue as long as the unreacted chemicals are added.

For example, a solution of silver nitrate added to a solution of sodium chloride will form poorly soluble silver chloride and soluble sodium nitrate. (Chemical reactions are expressed by means of balanced chemical equations.) Silver nitrate added to sodium chloride can be indicated by the following (see Figure 13-3):

$$AgNO_3 + NaCl \Rightarrow \underset{\text{(precipitate)}}{\underset{\Downarrow}{AgCl}} + NaNO_3$$

or more precisely,

$$\begin{matrix} Ag^+ \; NO_3^- \\ + Na^+ \; Cl^- \end{matrix} \Rightarrow \underset{\Downarrow}{AgCl} + Na^+ + NO_3^-$$

The silver nitrate and sodium chloride in solution have dissociated into their ions. When the silver and chlorine ions combine, they no longer exist as ions (are not dissociated), but form an insoluble precipitate that is removed from the reaction. Na^+ and NO_3^- ions remain in the solution.

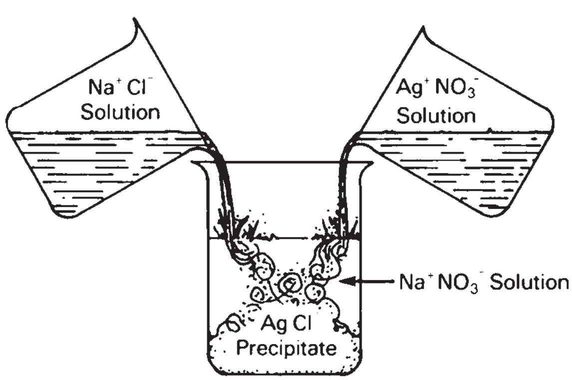


Figure 13-3 When clear, colorless solutions of sodium chloride and silver nitrate are added together a white insoluble precipitate of silver chloride is formed, along with a clear solution of sodium nitrate.

Oxidation/Reduction

Chemical reactions can take place without the ingredients being in solution—that is, between solids, liquids, and gases. When something burns, that means oxygen has combined with it, giving off heat at the same time. This is referred to as oxidation. Whenever oxygen unites with any other material, oxidation takes place. Oxygen is called the *oxidizing agent*. The material with which the oxygen combines is referred to as the *reducing agent*. Thus, reduction also occurs when a material takes on oxygen—one balances the other.

The oxidation/reduction concept can be applied to elements other than oxygen. Any element that gains electrons more rapidly than another element is said to have higher oxidizing power. Conversely, any element that loses electrons more readily than another element is said to have higher reducing power. When silver metal is subjected to chlorine gas, the two elements combine to form silver chloride (see Figure 13-4). This is an oxidation/reduction reaction where the silver is oxidized (and the chlorine is reduced), even though no oxygen is involved.

When treated with a reducing agent, such as a solution of ferrous sulfate, the silver chloride will be converted to metallic silver to form ferric sulfate and ferric chloride (see Figure 13-5). The iron, in oxidizing from the ferrous form with a valence of two (Fe^{++}) to the ferric form with a valence of three (Fe^{+++}), provides the

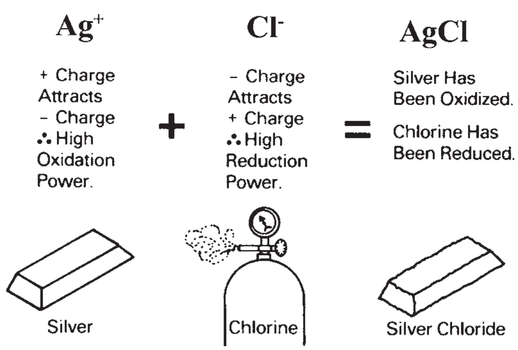


Figure 13-4 Oxidation occurs when a positively charged atom attracts a negatively charged atom, and reduction occurs when a negatively charged atom attracts a positively charged atom. In this reaction, silver has been oxidized, and chlorine has been reduced to form silver chloride.

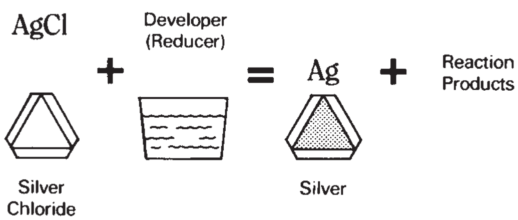


Figure 13-5 Silver chloride in a photographic emulsion is acted on by a reducer, the developer, to form metallic silver along with the other products of the reaction.

electrons that reduce the positive ionic charge of silver:

$$\begin{array}{ll} 3\ AgCl & \Rightarrow\ 2\ Fe(III)(SO_4)_3 \\ +\ 3\ Fe(II)SO_4 & \quad +\ 3\ Ag^o + Fe(III)Cl_3 \end{array}$$

Development of silver chloride occurs in a photographic emulsion, when a mild reducing solution, the developer, provides electrons that selectively reduce only that part of the silver chloride that has been exposed to light. The *latent image* is converted into a real, visible silver image. Oxidation/reduction concepts can become rather involved.

Acid/Base

An acid is a compound containing hydrogen ion and another element or ion. Hydrochloric acid, for example, is a compound containing hydrogen and chlorine, HCl. This is a strong acid. HCl can exist as a gas, but as an acid it is an aqueous solution of that gas in water. Sulfuric acid is made up of hydrogen ion and the SO_4^- ion (SO_3 [gas] + H_2O [water] = H_2SO_4 [sulfuric acid]). Like hydrochloric acid, this is also a strong acid, which means that it is highly ionized or dissociated in solution—that is, $H^+\ SO_4^-$, and H^+Cl^-. Acetic acid, an organic compound, CH_3COOH, is a relatively weak acid by comparison. Acids are formed when oxides of nonmetallic elements are dissolved in water, and bases are formed when oxides of the metallic elements are dissolved in water. Essentially, a base is a compound containing a hydroxyl (OH^-) ion and another element or radical. Calcium oxide, CaO, when dissolved in water, yields calcium hydroxide, $Ca(OH)_2$, a base. A *base* is also known as an *alkali*. Practically all developers are basic in composition. When placed in water, metallic sodium produces a violent reaction in which one of the hydrogen atoms of water is given off as a gas, which ignites from the heat of the reaction and burns, leaving a strong alkali, NaOH ($Na^+ + OH^-$), as shown in Figure 13-6. Ammonium hydroxide, NH_4OH, is also a base, and has the characteristic *ammonia* odor. (Ammonia with moisture, ammonium hydroxide, is the developing agent for diazo papers.)

When an acid and an alkali combine, water is formed along with a salt, gas, or precipitate.

Acids are sour to the taste (such as acetic acid, the chief component of vinegar). Bases are characterized by their "slippery" feeling. For example, a weak solution of lye, NaOH, feels very slippery, as do most developer solutions that contain an alkali. When an acid solution is combined with a solution of a base, in equal molecular

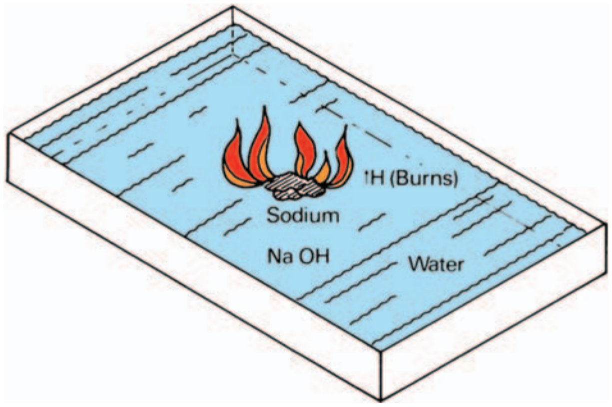


Figure 13-6 When the metal sodium is placed in water a violent reaction takes place in which one of the hydrogen atoms of water is released. The hydrogen burns while the remaining single atom each of oxygen and hydrogen combine with the sodium to form strongly alkaline sodium hydroxide.

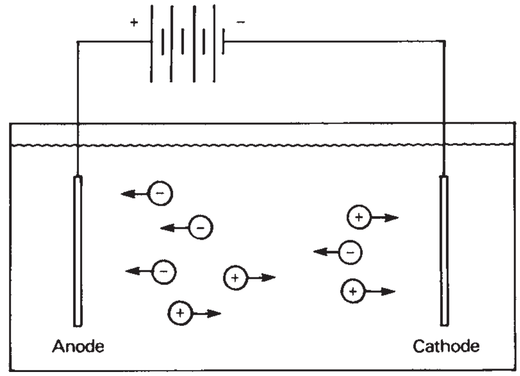


Figure 13-7 A solution of sodium chloride contains negatively charged chlorine ions and positively charged sodium ions. Electrodes placed in the solution and connected to a battery will cause the negatively charged ions to move to the anode where they lose their charge and become chlorine gas. The positively charged sodium ions will move to the cathode to form sodium metal, which reacts with the water to form sodium hydroxide and hydrogen gas.

amounts, a salt is formed. For example, if hydrochloric acid is added to sodium hydroxide, sodium chloride, a salt, and water are formed. The water of formation is simply added to the water containing the acid and the base:

$$HCl + NaOH \Rightarrow NaCl + H_2O$$
$$H^+ + Cl^- + Na^+ + OH^- \Rightarrow Na^+Cl^- + H_2O$$

Ionization

The atoms of salts dissociate when dissolved in water, forming negative and positive ions.

Acids have pH values below 7 and alkalis have pH values above 7.

Pure water is made up of equal parts of H^+ (hydrogen) and OH^- (hydroxyl) ions. When a salt is dissolved in water, it dissociates into the ions of the elements or polyatomic ions making up the salt. Sodium chloride, for example, ionizes into Na^+ and Cl^- ions. The presence of these free ions permits the passage of an electric current through the solution, and it becomes known as an electrolyte (see Figure 13-7). A solution of sugar, an organic compound that does not dissociate into ions, therefore does not carry an electric current.

pH

Chemists commonly specify the hydrogen ion concentration in terms of pH. pH is the negative logarithm of the hydrogen ion concentration. A strong acid with a hydrogen ion concentration of 10^{-2} (that is, 1/100) has a pH of 2, and a strong alkali with a hydrogen ion concentration of 10^{-12} (that is, 1/1,000,000,000,000) has a pH of 12. Pure water or a neutral salt solution that has an equal number of positive and negative ions has a pH of 7. The higher negative exponents, representing lower hydrogen ion concentrations, and thus higher hydroxyl concentrations, range from 7 through 14, and are the alkaline side of the scale. (D-72 developer for paper has sodium carbonate as the alkali, and a pH in the vicinity of 10.) Conversely, lower negative exponents, representing higher hydrogen ion concentrations, are on the acid side of the scale, and range from 1 through 7. (An acetic acid stop bath, for neutralizing the alkali of the developer after development, might

have a pH in the vicinity of 3.5.) Or this can be restated as follows:

$$pH = \frac{1}{\log(H^+)} \quad \text{or} \quad = -\log(H^+)$$

where H^+ is the hydrogen ion concentration.

pH Meters

Since pH indicates hydrogen ion concentration, it is also related to electrical potential. That is, if suitable electrodes are placed in such an ionized solution, it acts as a battery or galvanic cell, and produces a voltage, E. The relationship between pH and the voltage (or electrical potential) is rather complex, and therefore several qualifications have to be made when using this potential to measure pH. Since we are interested in the potential without the passage of current, which would have the effect of immediately lowering the voltage, the voltage is usually measured in comparison to a standard cell incorporated in the meter. Some modern meters, however, with very little internal resistance, are direct reading. The relationship between the measured potential and pH is as follows:

$$pH = \frac{(E - E_0)}{0.0591}$$

where E_0 is a constant.

pH meters are calibrated directly in pH values, and it is not necessary to read a voltage and then convert it to pH. The measurements are directly affected by temperature, which has to be taken into consideration and adjustments made if it is different from 25° C.

pH Indicators

Many dyes change their color under the influence of a particular pH condition.

Figure 13-8 Dye-treated pH indicator paper. A small strip of the paper is taken from the package and dipped in the solution to be tested. The dye in the paper changes color according to the pH of the solution. The pH value is then assessed by comparing it with the color references on the package.

These are referred to as *pH indicators*. Papers that have been impregnated with the dyes are available for indicating in various pH ranges (see Figure 13-8). These are generally more broad in their measure than pH meters, and there is a limit to the number of useful indicators that are available. Also, some judgment may be required in the interpretation of the colors produced. However, they are useful under many circumstances.

A pH meter is a voltmeter calibrated in terms of pH.

The performance of various photographic chemical solutions is influenced to a great extent by pH, and the control of this factor in one way or another is important. For example, the rate of development tends to increase as the pH, or alkalinity, of the developer is increased. Bleaches and other solutions used in color photography require control of pH to make sure that the bleaching action is adequate while at the same time dyes formed by the process are not adversely affected. The acid strength of stop baths and fixers has to be maintained to ensure that their neutralizing effects are adequate without producing other problems. Rate

Some dyes change color in response to a particular pH condition and can be used to measure pH.

of fixing, hardening, and stability of the fixing solution are influenced by pH.

Complexes

A *complex compound* is one that is made up of two or more compounds or compounds and ions. In the fixing process used in photography, for example, silver complexes are formed when the unexposed and undeveloped silver halide salt is treated with the fixing agent, sodium thiosulfate, $Na_2S_2O_3$. The fixing reactions pass through several complexes of varying solubility before one that is easily soluble is reached. The following represent several complexes that are part of the fixing reactions of silver halide photographic materials.

1. $2\ AgCl + Na_2S_2O_3 \rightarrow Ag_2S_2O_3 +$ NaCl (insoluble)
2. $Ag_2S_2O_3 + Na_2S_2O_3 \rightarrow 2\ NaAgS_2O_3$ (slightly soluble)
3. $4NaAgS_2O_3 + Na_2S_2O_3 \rightarrow$ $Na_6Ag_4(S_2O_3)_5$ (slightly soluble)
4. $Na_6Ag_4(S_2O_3)_5 + Na_2S_2O_3 \rightarrow$ $Na_5Ag_3(S_2O_3)_4$ (soluble)
5. $2Na_5Ag_3(S_2O_3)_4 + Na_2S_2O_3 \rightarrow$ $3Na_4Ag_2(S_2O_3)_3$ (soluble)

During the fixation process, different silver complexes are formed in sequence with increasing degrees of solubility.

When the silver halide has been converted to complexes 4 and 5, they can be washed out of the emulsion and/or paper to increase the image permanence. Complexes 1, 2, and 3, while they are transparent and give the film or paper the appearance of being fixed, are insoluble or only slightly soluble, and thus are not removed by washing.

When a substance, a solute, is dissolved in a solvent, a solution is formed.

The weight of a given volume of a substance compared to that of an equal volume of water is known as specific gravity.

Solutions

Most of the chemical processing of photographs is accomplished with various solutions. A solution consists of the solvent water in most photographic applications, with various chemical compounds dissolved in it. A chemical in solution is referred to as the solute. Various compounds have varying degrees of *solubility*—that is, capability of being dissolved in water, the solvent, until no more will dissolve. Such a solution is known as a saturated solution. The solubility of most chemicals varies with the temperature of the solution—a greater amount of the chemical can be dissolved in water at higher temperatures. When a solution has as much solute dissolved in it as is possible at a higher temperature, and the solution is cooled, the solute is thrown out of solution, usually in the form of crystals. A *supersaturated* solution is one that contains more solute dissolved in it than would normally be possible at that temperature. The addition of a small crystal of the solute, or some other disturbance, will cause the excess to be crystallized out rapidly. If a chemical compound in solution is mixed with another one also in solution, the product of the chemical reaction may be insoluble, and will be thrown out as a *precipitate*.

Other liquids can also be considered to be solvents, and indeed in chemistry there are many systems in which solvents other than water are used.

Rate of solution also depends on the size of the particles being dissolved, as shown in Figure 13-9. Small particles or crystals have a much higher ratio of surface to volume, hence the solvent can act over a larger area in a given time and thus the particles go into solution faster. (Extremely fine powders may provide excess surface and permit such factors as hydrolysis—reactions with water—to decrease solubility. The chemistry of solubility is complex and involves rates of diffusion, degree of dissociation, and many other factors.) Chemical compounds may

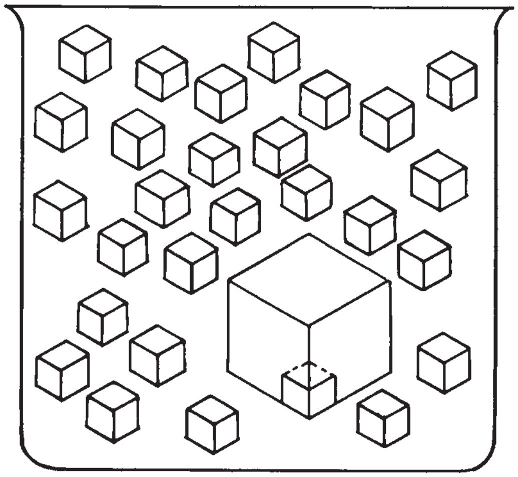


Figure 13-9 Volume of large cube (hence weight) is equal to that of all the smaller cubes, but surface area of large cube is one-third that of the smaller cubes.

either give off heat—*exothermic*—or absorb heat—*endothermic*—when they are dissolved. Anhydrous sodium thiosulfate ($Na_2S_2O_3$) gives off heat when it goes into solution but the compound of crystallization with water ($Na_2S_2O_3 \cdot 5H_2O$) absorbs heat when it goes into solution—that is, it is endothermic and the solution becomes cooler as the thiosulfate is dissolved. Monohydrated sodium carbonate ($Na_2CO_3 \cdot H_2O$) gives off heat when it is dissolved, and is thus exothermic—but sodium carbonate with 10 molecules of water of crystallization ($Na_2CO_3 \cdot 10H_2O$) absorbs heat, cools the solution, and is endothermic.

Specific Gravity

Specific gravity is the weight of a given volume of a substance, such as a solution, compared to that of an equal volume of water at a given temperature (which has to be taken into account for precise measurements). Specific gravity can be measured with a hydrometer, a graduated weighted tube that floats to a greater or lesser degree depending on the specific gravity of the solution in which it is floated. Specific gravity is read from a scale inside the tube.

REVIEW QUESTIONS

1. An element that is not a member of the halogen family is . . .

   A. chlorine
   B. fluorine
   C. helium
   D. iodine
   E. bromine

2. Atoms normally have . . .

   A. a positive electrical charge
   B. a negative electrical charge
   C. a neutral electrical charge

3. The chemical formula for water is H_2O. If it is known that hydrogen has a valence of 1, it can be assumed that oxygen has a valence of . . .

   A. 0
   B. 1
   C. 2
   D. 3
   E. 4

4. The light-sensitive compound silver bromide (AgBr) could be produced with a chemical reaction between . . .

   A. silver nitrate and sodium chloride
   B. silver chloride and sodium nitrate
   C. silver nitrate and silver bromide
   D. silver nitrate and sodium bromide

5. Developers for black-and-white films and papers are . . .

   A. reducing agents
   B. oxidizing agents
   C. nonparticipatory agents

6. A tray of developer could be identified by touch in a darkroom sink that also contained trays of stop bath, fixer, and water because the developer would feel . . .

   A. warm
   B. slippery
   C. sticky
   D. stingy
   E. gritty

7. An ion is an atom that has . . .

   A. no electrical charge
   B. a positive charge
   C. a negative charge
   D. either a positive or a negative charge

8. A photographic processing liquid that has a pH of 9 is probably . . .

   A. a developer
   B. a stop bath
   C. a fixing bath
   D. a hypo clearing agent bath
   E. the wash water

9. Indicator papers identify pH by means of a change in . . .

   A. lightness
   B. hue
   C. conductivity

chapter

14 Photographic Emulsions, Films, and Papers

Photograph by Josh Shagam, Biomedical Photographic Communications student, Rochester Institute of Technology.

Photographic Emulsions

A photographic emulsion consists of silver halide crystals suspended in gelatin. The emulsion is usually coated on a support that may be clear, as in the case of negative films, or opaque, as for photographic prints. The emulsion has the most significant controlling effect on the photographic and physical properties of the final product.

Silver is used in photographic emulsions because its compounds are more sensitive to light than any other photochemical material.

Cellulose nitrate, which is chemically similar to guncotton, was not the safest support for photographic films.

To visualize the emulsion, think of a chocolate candy bar with peanuts imbedded in it as shown in Figure 14-1. The peanuts are suspended in the chocolate medium. Similarly, the silver halide particles are suspended in gelatin. There are many different recipes for making photographic emulsions. Choice of gelatins and different combinations of salts (sodium, potassium, ammonium, or calcium and chloride, bromide, or iodide, for example), along with other chemical ingredients, impart characteristics to the emulsion such as speed, spectral sensitivity, contrast, resolution, graininess, and physical properties. The emulsion is applied to the film or paper in a liquid state, and thickness of the emulsion layer is adjusted by controlling viscosity and speed of coating. The gelatin is then chilled (just as a gelatin dessert is when placed in the refrigerator), and then slowly dried to remove most of the water.

The silver halides respond to light to produce a latent image that is later developed to produce a visible silver image. The gelatin also acts as a binder, serving to protect the silver halide from abrasion and other mechanical and chemical influences, and in some cases the gelatin can even serve as the support for the image. Through impurities and other characteristics, the gelatin contributes to the photographic and chemical performance of the silver halides in the emulsion. Silver is used because its compounds are more sensitive to light than any other photochemical material.

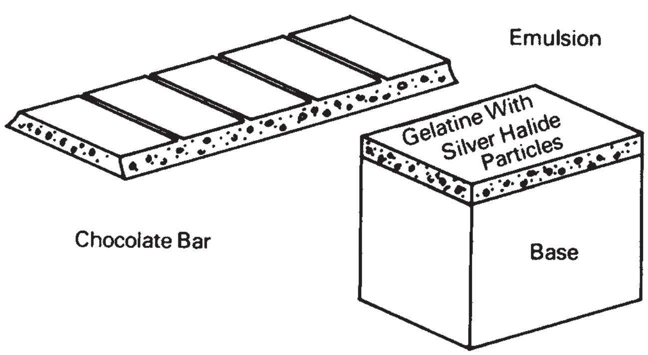


Figure 14-1 The photographic emulsion can be compared to the chocolate nut bar. The nuts are suspended and separated by the chocolate as the silver halide grains are in the emulsion.

Safety Base Films

Very early cellulose nitrate film bases were highly flammable. Frequent fires occurred where large amounts of film were stored, such as movie theaters and X-ray films in hospitals. The Eastman Kodak Company developed a nonflammable cellulose acetate safety film very early in the 1900s, but it was not accepted by the motion picture industry because of cost; and some of the other physical characteristics, such as wear on repeated showings, were not as good as those of the nitrate film. With more experience and further research and development, improved versions of acetate films were produced, and they are still the best support for commercial motion picture film.

Nitrate base of greater thickness was also used for early sheet films, replacing glass plates. These nitrate films were supplanted by acetate bases when this type of material became available. While acetate bases had better dimensional stability during processing and storage than did nitrate bases, they were still far from ideal for some applications. They were less flexible, more brittle, and did not wear as well as the nitrate films.

Polyester Film Bases

In recent years many of the products previously manufactured with acetate base have been produced on polyester bases, which are made in an entirely

different manner. These are manufactured by extruding the heated polyester material through a slot, stretching it in a longitudinal direction at the same time that it is stretched by means of grippers in a widthwise direction while still heated and soft, as shown in Figure 14-2. This orients the molecules of plastic, yielding a base material that is free from stresses and strains, and that has very good dimensional stability and certain other characteristics.

One problem with this type of base is the need of a suitable subbing so that the emulsion will adhere properly during the life of the material. While the techniques of subbing for good adhesion have been perfected for the old solvent cast base materials, there have been some lingering problems with the newer polyester materials, leaving some doubt as to their suitability for archival storage of images. These problems have been resolved, and newer polyester materials are considered to be suitable for archival storage. Another early problem with the polyester films for motion picture applications was that of splicing, but this has been solved by new heat and tape splicing techniques (in those applications where the stronger base might be required).

Such polyester films can act like fiberoptics and pipe light in a transverse direction, thus not serving well as a self leader when the film itself is intended to protect the image forming part of the film from ambient light when on a daylight loading spool. In many applications, light piping of films is eliminated by introducing dyes or pigments into the base itself, as shown in Figure 14-3. Some light is absorbed in the viewing direction, where the density of the base may be on the order of 0.1 to 0.2, and the thickness of the base may be around 0.002 to 0.004 inch. In the crosswise direction, the density adds up very rapidly, and thus absorbs most of the light traveling in this direction.

Polyester films also have a greater tendency to generate static electricity—they are good insulators—and this

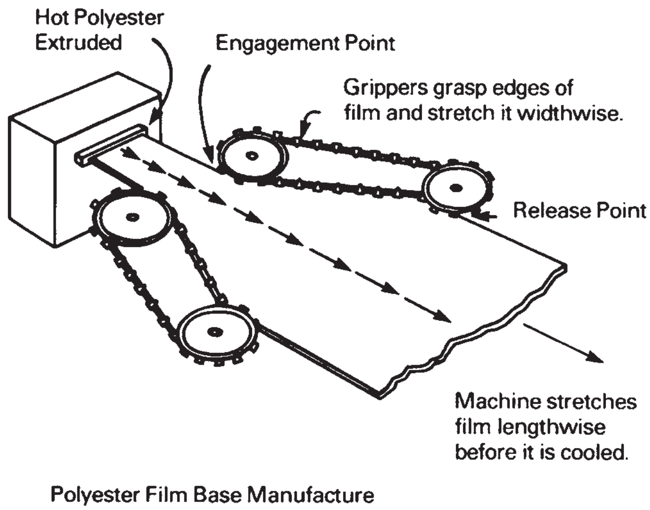


Figure 14-2 Polyester film base manufacture.

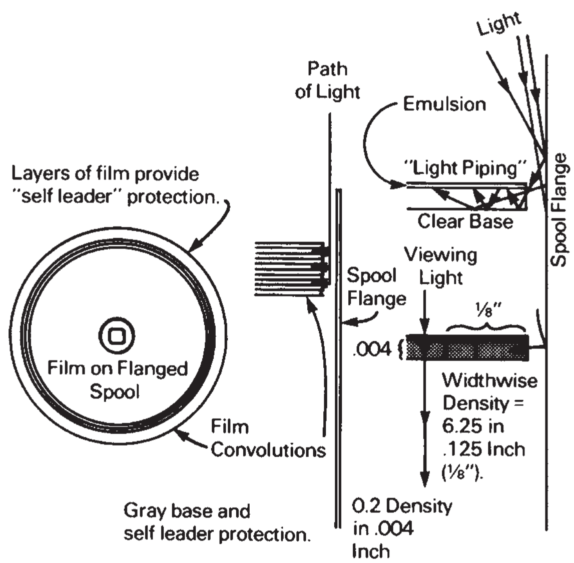


Figure 14-3 Daylight loading spools depend on the protection provided by several convolutions of film (4 to 7 feet in length). The necessary light stopping density is provided by the combination of emulsion, antihalation protection, and base density. Light entering between the film and the spool flange may be decreased by incorporating a pigment or dye in the base. The density in the viewing direction is relatively low, but adds up rapidly in the widthwise dimension.

Polyester film base materials have high strength, good dimensional stability, and other desirable characteristics, but they also tend to generate more static electricity, scratch more easily, and pipe light in from the edges.

The resin coating on the paper base of RC papers protects it from processing solutions and therefore shortens processing time.

makes them more susceptible to picking up dust and lint from the atmosphere. They are also more susceptible to scratching, and readily show scratches on viewing the photographic images if the base is not protected by a gelatin NC (non-curl) or antihalation coating. In the beginning, their very high tensile strength prevented them from breaking when trouble occurred in processing machines and similar equipment, and therefore the machinery was damaged rather than the film. The solvent cast acetate types of film are still largely used for commercial and motion-picture applications, and for most roll films.

Film Structure

A photographic film can be very simple in structure—a coating of a gelatin—silver halide emulsion on a transparent base, such as positive film, used for printing black-and-white motion pictures. Negative films used for pictorial photography are generally more complex in their structure. In many films two or more coatings of emulsion are used to derive the sensitometric characteristics that yield good pictorial tone rendition. On top of this there is generally an overcoating or surface layer that controls many of the physical characteristics of the film.

Paper Bases

Most photographic prints are made on some form of paper base. Traditionally this type of base was manufactured with pulp made from old rags, but in more recent years practically all of it has been made from a high-quality wood pulp (alpha cellulose). These are referred to as fiber-base papers. Many photographs are made on paper that has been coated with a plastic or resin (such as polyethylene) on both sides. These are referred to as RC (resin-coated) papers. The resin surface coating of the stock protects it from the chemical solutions and water of processing, so that processing, washing, and drying times can be much shorter than with the fiber-base papers. Because of the problems of emulsion adhesion to polyethylene coatings, fiber-base papers are still preferred for producing photographs with archival permanence.

Several paper surfaces are produced by embossing the stock with an engraved roller under pressure to impart a distinctive textured surface pattern. These patterns can be irregular, but some are geometric in nature, for example, “silk” and “linen” surfaces. Any of the above can be coated with one or more layers of barium sulfate (baryta) and/or other white pigments (sometimes before embossing) before coating with photographic emulsion. This imparts a better, brighter color to the base, and also limits the penetration of the emulsion into the base, which gives a more uniform coating and a more even image, with more uniform blacks. The nature of the baryta coating also affects the reflectivity of the coating’s surface. The baryta coating is omitted from photographic papers that may be folded in use, to prevent the emulsion layer from cracking.

Brighteners

It is common to incorporate optical brighteners in both nonbaryta-coated and baryta-coated paper surfaces, producing the effect of intensifying the paper’s brightness. These are similar to laundry brighteners. The effect is

produced by using a dye or other substance that fluoresce upon exposure to ultraviolet energy (available to some extent from most light sources) to convert the invisible ultraviolet radiation to light.

Paper Weight and Thickness

Photographic papers are manufactured in various "weights." These are referred to in such terms as *single weight, document weight, light weight, medium weight*, and *double weight* (see Figure 14-4). Paper stock is customarily manufactured, controlled, and sold in terms of weight, but photographers are more aware of the different thicknesses of photographic paper bases. Hence, international standards designate papers in terms of their thicknesses. American National Standard PH1.1-1974, *Thickness of Photographic Paper, Designation For*, lists nine groups of paper thicknesses, with ranges for each group both in English and in metric units, and gives common trade designations (in terms of weights) for each of the groups.

A standard on photographic papers lists nine different categories of paper thickness.

The Gelatin Colloid

Gelatin is a colloid. A colloid is a particulate material that can be suspended in water or other solute without settling out. The sizes of the particles range from approximately 1 to 1000 nm, or intermediate between visibly suspended particles and invisible molecules. (One nanometer is one billionth of a meter, or one millionth of a millimeter.) Other colloids have been used for photography, and colloids that are a more similar substitute for gelatin have been tried, but gelatin has been, is, and will continue, for the near future at least, to be the best material for the preparation of photographic emulsions. (Albumen and collodion are examples

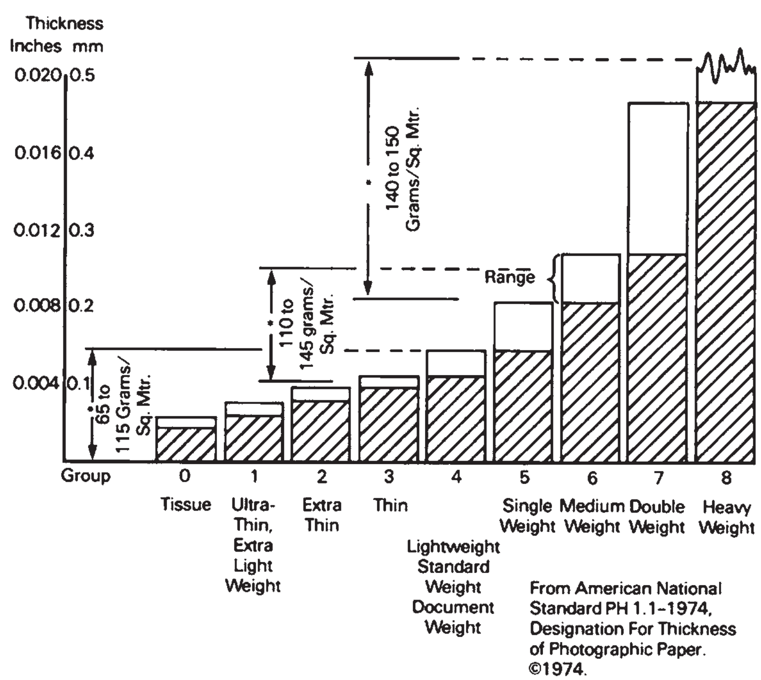


Figure 14-4 Paper thickness.

An important feature of gelatin is that it has a large molecular structure.

Photographic gelatin has many desirable characteristics in addition to being transparent.

Gelatin tolerates both acid and alkaline solutions, prolonged washing, and changes in temperature.

of other colloids that have been important in photography.)

Properties of Gelatin

The gelatin colloid used to make photographic emulsions has several important properties:

1. Gelatin disperses the light-sensitive silver halide crystals and prevents them from adhering to one another, or coagulating, and thus forming, in effect, larger crystals or grains.
2. When wet, gelatin can be changed to a solid gel or liquid reversibly by changing the temperature.
3. When dry, gelatin is reasonably stable, and thus protects the silver halide grains.
4. Gelatin serves as a receptor for halogen atoms in some aspects of latent image formation.
5. Gelatin has no effect on the silver halide, other than the protective function, although impurities found in many gelatins contribute to the photographic result (sensitivity, fog, etc.), sometimes beneficially, at other times in a manner that degrades the image.
6. Gelatin permits the processing solutions to penetrate and chemically react with the silver halide grains in development, fixing, etc.
7. Gelatin can be produced uniformly and inexpensively, and stored for long periods prior to use in manufacture.
8. Gelatin is transparent.

To help ensure uniformity, numerous batches of gelatin of a given type are blended so that when a new batch is added it contributes only a relatively small amount to the overall characteristics of the blend. (American table wines are often blends of various batches of grapes for the same reason.)

Chemical Nature of Gelatin

Gelatin is an organic compound or, more precisely, a group of compounds (they are derived from organic materials—living animals—and can be burned) largely made up of carbon, hydrogen, oxygen, and nitrogen atoms having a composition of approximately 50, 7, 25, and 18 parts of these atoms, respectively. It has a very complex molecular structure made up of various amino acids. The average molecular weight of gelatin is about 27,000 or some multiple of this. (Molecular-weight values determined in a variety of different ways have ranged from 768, corresponding to a formula $C_{32}H_{52}O_{12}N_{10}$, to 96,000.) Since the amino acid molecules contain both acid carboxyl groups and basic amino groups, they are *amphoteric*—that is, they can act either as an acid or a base. Since the acidic and basic characteristics are not strong, it acts as a buffer. Large additions of either an acid or a base do not have a large effect on the hydrogen ion concentration (pH).

Physical Properties of Gelatin

Dry gelatin contains about 10% water and is a tough material with great mechanical strength. To prepare an emulsion, dry gelatin is soaked in water, which penetrates into the gelatin structure and causes it to swell many times its original dimension. When thus wet, it is soft and easily damaged.

When the soaked gelatin is heated to about 40° C (100° F), it melts and can be further diluted with water indefinitely. If the concentration of gelatin in water is greater than 1%, it will set when cooled, just as dessert gelatin does, to become a gel that can

be dried with dry air without remelting. Before drying, the set gelatin can be remelted by raising the temperature, and reset by cooling, repeatedly but the setting and melting temperatures do not coincide.

Emulsion Making

Throughout the history of photography, the theory of the emulsion-making process has been difficult to understand. The characteristics of the final emulsion are governed by many factors, including the choice of soluble halides and gelatin, the method of silver halide precipitation, the cooking or ripening processes, and the choice of chemical additives to the emulsion. Since many of these processes cannot be patented, photographic manufacturers take great pains to maintain the secrecy of their emulsion-making techniques. The following basic considerations, however, are well known. The basic emulsion-making steps for a typical black-and-white film emulsion are precipitation, ripening, washing, digestion, additions, and coating.

A photographic emulsion is formed by treating a soluble silver salt with a soluble halide or halides in the presence of gelatin in solution; for example,

$$AgNO_3 + KCl \rightarrow AgCl + KNO_3$$

Silver nitrate plus potassium chloride yields silver chloride plus potassium nitrate.

The light-sensitive silver halide, in this example silver chloride, exists in the form of crystals or grains that are one micrometer (one thousandth of a millimeter) in diameter or less. Mixtures of halides (chloride, bromide, iodide) are commonly in the form of mixed crystals containing two or three halides in each crystal (see Figure 14-5).

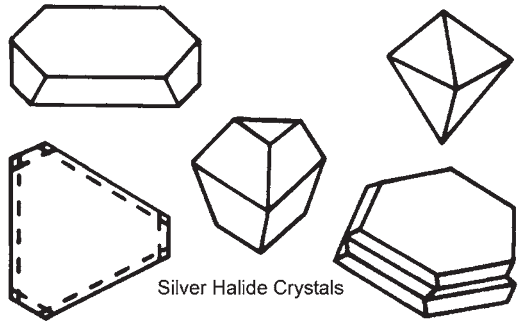


Figure 14-5 Silver-halide crystals.

The gelatin acts as the protective colloid in that it prevents the crystals from coalescing, and also controls the size and distribution of the crystals to some extent. Silver halides are primarily sensitive to ultraviolet radiation and blue light. Small amounts of compounds that react with the silver halide to increase sensitivity may be present in the gelatin, or they may be added separately to inert gelatin. Dyes may also be added to extend sensitivity to other regions of the spectrum than the ultraviolet and blue.

Basic emulsion making consists of precipitating a silver halide in a gelatin solution.

The size and size distribution of silver halide grains have an important effect on the sensitivity and contrast of photographic emulsions.

Emulsion Characteristics

The photographic properties of an emulsion depend on a number of factors including its silver halide composition; the shape, average size, and size distribution of the crystals, and the presence of substances that affect sensitivity. All of this is governed by the amount and kind of gelatin(s) in the original solution, the choice of halide compounds, the way in which they are mixed together, the way they are treated following this precipitation, what other substances are added, and the coating procedure. These factors control photographic properties such as the speed, characteristic-curve shape, spectral sensitivity, and exposure latitude of the emulsion and image characteristics such as graininess, sharpness, and resolving power.

Controls such as choice of silver halides, type of gelatin, method of mixing, additives, and cooking time make it possible to produce a great variety of film and paper emulsions.

Grain Size, Sensitivity, and Contrast

The grains of the emulsion can be considered as individual units as far as exposure and development are concerned. A latent image formed in one of the grains does not ordinarily spread to the other grains unless they are touching. For a given exposure there is a greater probability that a large grain will absorb a quantum of light than will a small grain. If the grains were uniform in size, and in a single layer (one grain thick), the probability that individual grains would be exposed and made developable would depend on the random distribution of photons reaching the grains. Since such grains are uniform in size, density after development will vary with the fraction absorbing at least the number of photons required to become developable. When several photons are required, most of the grains will receive enough at the same time and thus the characteristic curve will have a steep slope, indicating high contrast. The toe of the curve represents the region of exposure where only a small fraction of the grains receive enough photons to become developable.

If the grains are large, they provide a greater area for receiving photons, are thus more likely to be exposed, have a greater number of silver ions available for reduction, and after development they have a greater light-absorbing capability. This has the effect of giving the larger grains a greater amplification effect than smaller grains.

Intermediate-size grains would produce an amplification effect between those of the largest and smallest sizes (see Figure 14-6). Emulsions with a wide variety in grain sizes will have inherently lower contrast than emulsions having equal grain sizes, and will have greater sensitivity due to the availability of larger grains. The resulting characteristic curve will have a lower slope than in the case where the grains are all nearly the same size.

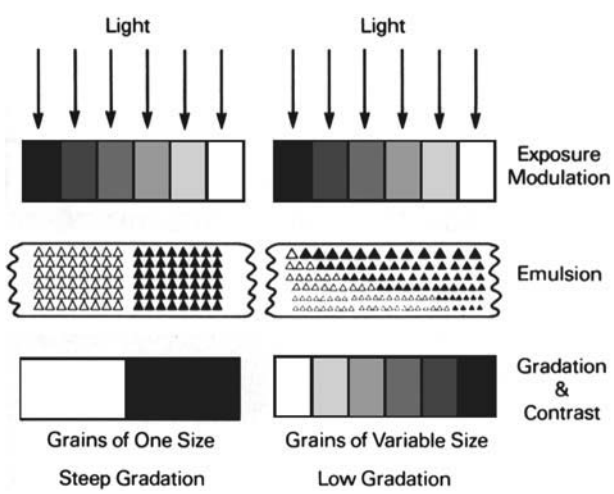


Figure 14-6 Emulsions having grains of nearly equal size will produce steep gradation, while those having a wide variety of grain sizes will produce low gradation.

Grain Composition

The composition of the silver halide grains plays an important part in the emulsion. The presence of iodide in small amounts enhances the sensitivity of silver bromide grains. The composition of the grains formed by precipitation of a silver salt and two or three halogen salts depends on the solubility characteristics of the precipitated halides. The three light-sensitive silver halides used in photography are relatively insoluble compared to the salts from which they are formed.

The overall solubility of the silver halides in emulsions is increased by virtue of the small size of the crystals, 1 micrometer or less, which increases the surface-to-weight ratio significantly. This difference in solubility according to grain size accounts for the increase in average grain size during ripening, in which the smallest grains

become smaller and the dissolved silver halide comes out of solution as an addition to the larger grains.

Spectral Sensitivity

The fine division of halides in emulsions provides a greater amount of surface for adsorption of materials to the silver halide grains. Adsorption is the adherence of atoms, ions, or molecules to the surface of another substance. First, silver halide grains adsorb additional halide ions, with the greatest adsorption occurring with iodide and the least with chloride ions. In addition, the grains adsorb gelatin, sensitizing dyes, and other compounds. These all contribute to the overall sensitivity of the emulsion. The silver halide grains themselves have varying sensitivities to light of different wavelengths, depending on the halide. Silver chloride, which is colorless, is sensitive at the shortest wavelengths, mostly ultraviolet energy, extending up to about 420 nm. Silver bromide, which is more yellowish in appearance, has sensitivity extending to about 500 nm. Additions of iodide, which has a strong yellow color, in amounts ranging from 0.1% to 1.0% of the chloride crystals, extends the sensitivity to 450 to 475 nm. A similar extension is achieved when about 40% bromide is added to chloride. Bromide with about 3% iodide extends the sensitivity to about 525 nm (see Figure 14-7). Even without further extensions of sensitization, such as with dyes, the safelight filter must not have any transmission below 550 nm.

Silver bromide, chloride, and iodide have different ranges of spectral sensitivity in the short wavelength part of the spectrum.

Crystal Structure

Defects in the crystals of silver halides are an important aspect of light-sensitive emulsions. Silver halide crystals are usually composed of ions in a cubic lattice so that each halide ion is surrounded by six silver ions, and each silver ion is surrounded by six halide ions, as shown in Figure 14-8. This arrangement can exist within the interior of the crystal, but at the outer surface there has to be one of each with only five of the other surrounding it. Even in the cubic system, crystals can be formed that are octahedral in shape, or in the form of hexagonal plates (see Figure 14-5). Different photographic effects are produced by the surfaces presented by these different crystal shapes.

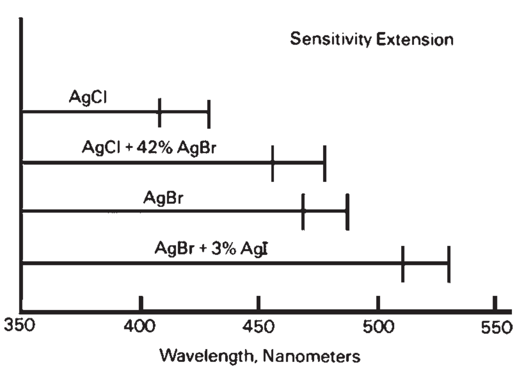


Figure 14-7 In silver halide emulsions, grains of silver chloride are sensitive to the shortest wavelengths of light, silver bromide to considerably longer wavelengths, and combinations of bromide and iodide to the longest wavelengths. (Chateau et al., *The Theory of the Photographic Process*, 1966, p. 6.)

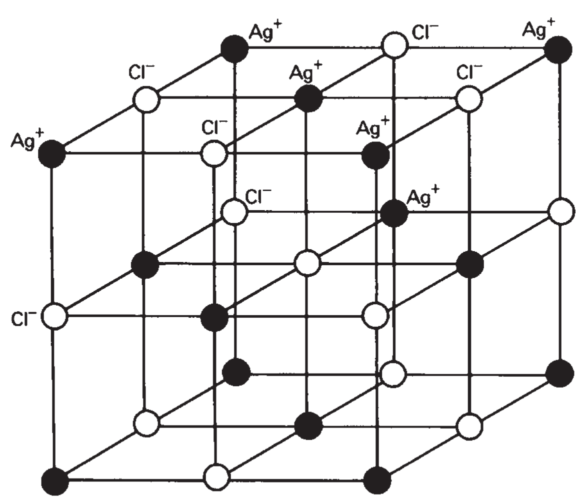


Figure 14-8 Structure of silver halide crystal.

The shape of silver halide crystals and the presence of defects in the crystals affect the photographic characteristics of the emulsion.

The rate of mixing emulsion ingredients affects the speed and contrast of the emulsion.

Defects

The defects in the crystal lattice can be divided into extended imperfections and point defects. Whereas the faces of the crystal have only five ions around each one of opposite charge, at the corners there can be only three, and at the edges only four. Adsorption is greater at these positions and reactions may begin here. These positions are supplemented by other dislocations that can occur in the crystal's formation. All are important in the photoconductive and photochemical processes. The most important type of point defect is interstitial silver ions—a minute fraction of the silver ions escape from their positions in the crystal lattice and can move through the spaces in the lattice, as shown in Figure 14-9.

Defects in the crystal act as locations for the formation of sub-image centers during latent image formation. Silver and halogen ions are not free to move, except to adjacent positions in the lattice, but electrons are free to move throughout the crystal. These motions manifest as electrolytic conductivity, which plays an important part in the photolytic process. One kind of defect arises from a vacancy in the crystal lattice, such as would occur if a silver ion were removed to an interstitial position. This would leave a silver ion vacancy that would have a negative charge. The interstitial silver ion itself would have a positive charge. An extra electron would produce a negative charge, and a positive charge would occur when an electron is removed from the valence band of the crystal.

Emulsion Precipitation

A typical emulsion-making process starts with a relatively dilute solution of gelatin in water (about 1%). Soluble halide salts (one or more) are added to this solution (potassium, sodium, or ammonium chloride, bromide, or iodide), as shown in Figure 14-10. Then, at a selected temperature, a soluble silver salt, such as silver nitrate, is added at a controlled rate and with controlled stirring. The silver halide or halides are precipitated out, and the crystals are first formed in a strong solution of soluble halide, in which the silver halide is much more soluble than in pure water. Under these conditions, the crystals first formed grow rapidly and continue to grow throughout the precipitation.

Even a relatively dilute gelatin solution provides protection to the silver

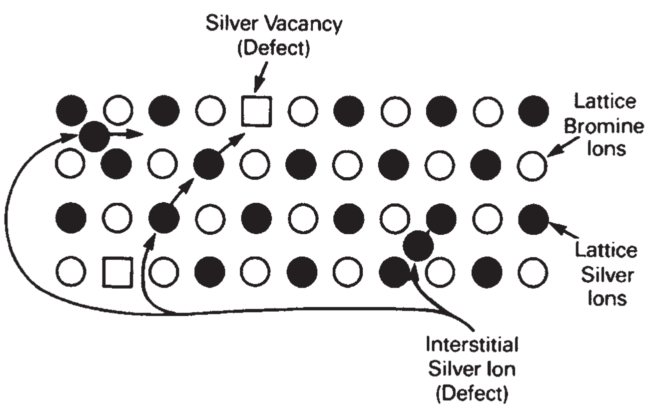


Figure 14-9 The point defect of interstitial silver ions in a silver-halide crystal. Lattice ions themselves cannot move throughout the lattice, but an interstitial ion (defect) can. It can also push a lattice silver ion to a new position.

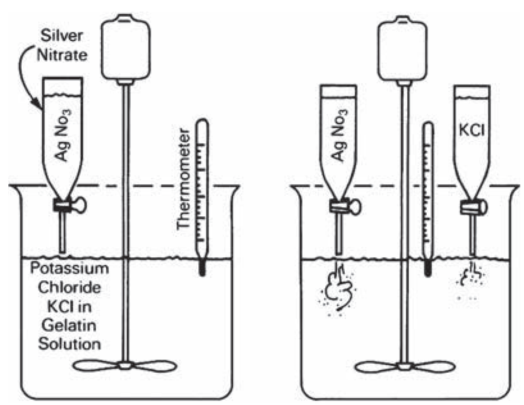


Figure 14-10 Emulsion precipitation.

halide crystals formed. If it were not for the gelatin, the particles of the precipitate would coalesce and rapidly fall to the bottom of the reacting vessel. The growth of crystals to grains of the desired size with good structure would be difficult.

Washed Emulsions

When an emulsion is coated on a porous support, such as a baryta-coated or otherwise uncoated paper base, the excess alkali nitrate after the precipitation reaction can be absorbed by the base. If the base or support is a film, or a paper base with a water-impermeable surface such as resin coated (RC), these excess salts have to be removed by washing to prevent them from crystallizing out on the surface (see Figure 14-11). It is also desirable in the emulsion-making process to remove excess salts to prevent further growth of the silver halide grain before continuing the process. This is accomplished by *coagulating* the gelatin, washing the emulsion, then re-dispersing (dissolving) the gelatin and halides. At its isoelectric point,

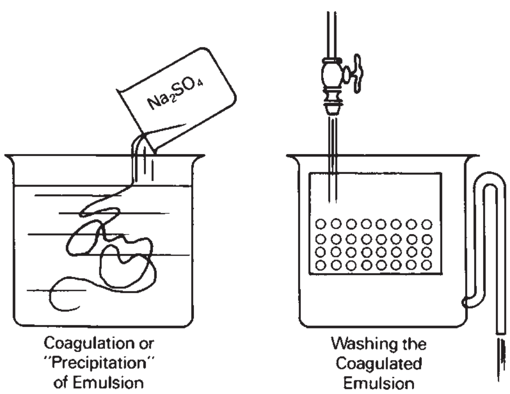


Figure 14-11 The gelatin emulsion is coagulated while at its isoelectric point by the addition of a salt solution such as sodium sulfate. It is then washed to remove the salts including those that were formed during the emulsion-making process. The washed grains can then be redispersed by raising the pH, along with the addition of more gelatin.

the gelatin can be coagulated by adding a salt such as a sulfate. There are also other methods of accomplishing this coagulation.

Historically the emulsion, with added gelatin, was chilled and set in a manner similar to setting food dessert gelatin. This set emulsion was then extruded into noodles, or sometimes cut into cubes (the noodling procedure was established by F.C. Wratten—of Wratten Filters—around 1878), and washed with chilled water until conductivity or pH tests showed that enough of the soluble salts had been removed.

After the precipitation and ripening steps, excess soluble salts are removed by washing to prevent crystallization and excessive growth of the silver halide grains.

Multiple Coatings

To achieve the desired sensitivity and tone-reproduction characteristics, black-and-white films often will have two different emulsions coated on top of the other. A slow, relatively short scale, or high gamma emulsion, is coated first, then a faster, coarse-grained, long-scale emulsion is coated on top of it to provide a characteristic curve with increasing slope in the upper midtone or lower highlight regions (see Figure 14-12). This provides better speed and scale characteristics than would be achieved by blending the emulsions. Color films are made up of at least three emulsions, one for recording each of the primary colors—red, green, and blue. One or more of these three, in turn, may be made up of multiple coatings to provide required tonal response, such as required by internegative films and those for other special applications.

Multiple emulsion coatings are used on some black-and-white films to modify the tone-reproduction characteristics of the film.

Effects of Development on Developers

The reaction products of development include soluble salts of the halides,

Dye-sensitized emulsions become sensitized to the colors of light that are absorbed by the dyes.

It is possible to dissolve all of the silver-halide grains in an exposed film with hypo without destroying the latent image.

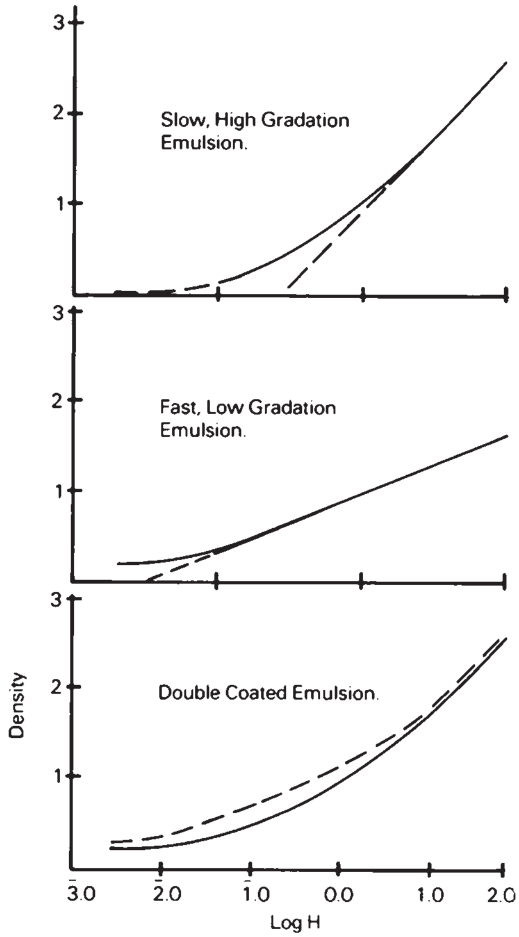


Figure 14-12 By coating a fast, low gradation emulsion over a slow, high gradation emulsion, the combination produces a sensitometric curve with increasing slope in the upper mid-tone and lower highlight regions.

along with modified developer components. The soluble halides act as restrainers, and thus curtail development. The kind and quantity of restrainer included in the developer formula is intended to minimize, as far as practicable, the effects of these reaction products of development.

Dye Sensitization

The basic silver halide emulsion is sensitive only to the blue and ultraviolet regions of the spectrum (about 180 nm to 520 nm) that it absorbs. The human visual response is highest in the green region, with a peak in the vicinity of 550 nm. Thus, photographs made with an unsensitized emulsion will have different black-and-white rendering of the brightnesses of colors than that perceived with the human visual system.

In 1873, the photographic scientist H.W. Vogel found that emulsions could be made to respond to wavelengths of light in the green region of the spectrum by adding a pink or red dye. The emulsion became sensitized to the color absorbed by the dye. When an emulsion sensitized to green by means of a red dye is used in the camera, with a yellow filter over the lens to absorb some of the blue light (to which the film remains sensitive), it gives a response in terms of black-and-white rendering that is somewhat closer to that observed by the eye and is thus described as an *orthochromatic* or "correct" color rendering. The term *isochromatic* has also been used to identify this characteristic.

Later, a green or cyan dye that absorbs red light extended the emulsion's sensitivity. Thus the emulsion is sensitized to red light by the addition of a cyan (red-absorbing) dye. Combined with the added green sensitivity, the emulsion responds to all of the colors of the visible spectrum, which includes blue, green, and red, and is termed *panchromatic* (see Figure 14-13). Spectral sensitization, while used in films mostly to provide appropriate tone reproduction of subject colors, also increases the film speed with white light, and some higher-speed films have a greater-than-normal sensitivity to red light.

These sensitizing dyes are sometimes retained by the film after processing, especially if a rapid processing technique is used, giving black-and-white

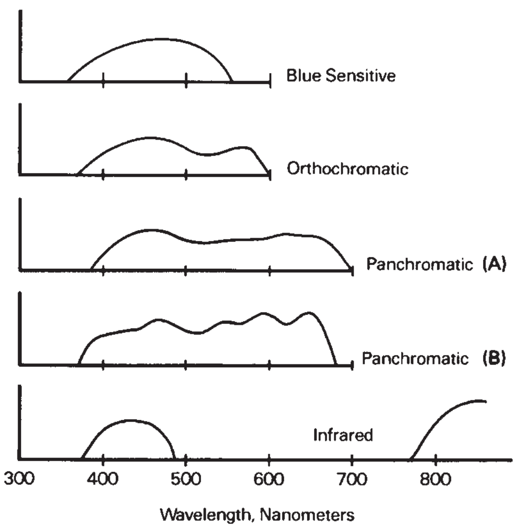


Figure 14-13 Traces from spectrograms for typical blue sensitive, orthochromatic, panchromatic, and infrared films. Panchromatic (A) has extended red sensitivity to nearly 700 nm; Panchromatic (B) is more representative of that used for pictorial photography.

negatives a pink cast. Normal development, fixation, and washing usually remove nearly all of the sensitizing and antihalation dyes from the negatives.

While most photographic papers are manufactured with emulsions that have been made to meet the sensitometric requirements without further modification, some papers require a final speed adjustment that can be achieved by addition of sensitizing dyes to the emulsion. This extends the sensitivity to some of the longer wavelengths of light. This technique can be satisfactory until a change in the color of the light sources used for printing or recording reveals a greater-than-expected shift in speed from one emulsion coating to another. Some variable-contrast papers have mixed emulsions of different contrast with spectral sensitivities that can be used to control the contrast by changes in filtration. A typical variable-contrast enlarging paper produces high-contrast images when exposed with blue light (with a magenta filter), low-contrast images when exposed with green light (with a yellow filter), and medium-contrast images when exposed with white light.

Formation of the Latent Image

After the sensitized material is exposed in a camera, examination of the surface would not reveal an image. It is said to be a *latent image*. Some of the chemical characteristics of this image are as follows:

1. It is weakened or destroyed by oxidizing agents such as chromic acid, which also oxidize metallic silver.
2. This oxidizing reaction does not destroy the sensitivity of the emulsion, which after washing and drying can be used to expose a new image, although spectral sensitivity and speed may be degraded.
3. It is not soluble in silver halide solvents. (If the exposed image is bathed in sodium thiosulfate solution and the remaining silver and halide ions are removed by subsequent washing, physical development can then be used to develop the latent image. Silver metal from silver ions in the developing solution plates out on image areas where exposure occurred.)
4. The reduction of silver ions to silver metal by the developer is catalyzed by the presence of silver atoms. The latent image also increases the reduction of silver ions.

From the above it appears that the latent image and silver have the same reactions. This indicates that exposure sets into operation a mechanism within the crystal that in the end produces silver atoms, which distinguish

It is thought that a latent image must contain at least four atoms of silver to be stable and developable.

exposed silver halide grains from those that are unexposed.

Thus, when the crystal of silver halide, made up of silver and halogen ions, is exposed to light, it becomes capable of being reduced by a developer to metallic silver, which along with all the other exposed crystals forms the image of the photograph. Among several theories that have been proposed for the mechanism of latent image formation, the Gurney-Mott hypothesis is a prominent one. It consists of two distinct steps in an exact order, but concluded in a short time interval. Using silver bromide as an example, they are:

1. The radiation of the silver bromide crystal produces electrons that are raised to a higher energy level associated with the conductance band. The electrons move through the crystal by photoconductance until they are trapped by the sensitivity specks. The specks, or traps, then possess a negative electrical potential. This concludes the primary process, and its final effect is to initiate the secondary process.
2. The secondary process involves the movement of the interstitial silver ions that are attracted to the negatively charged specks. The positive silver ions are neutralized by the negative charges, and the production of silver atoms is completed.

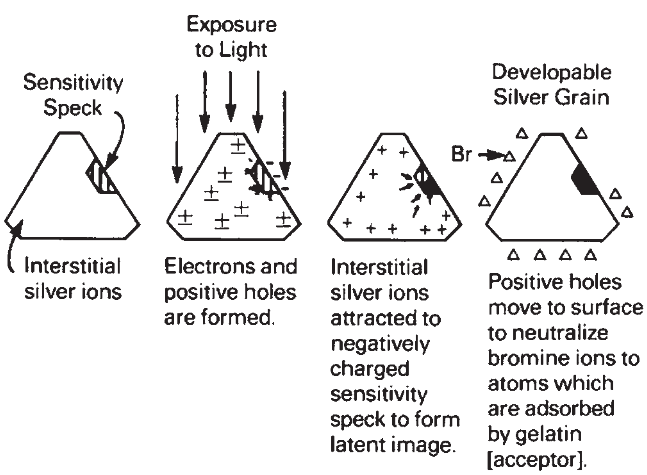


Figure 14-14 Gurney-Mott theory for latent image formation.

The hypothesis does not explain the fate of the halogen. It is possible that the halogen atoms may either recombine with an electron, may attack the silver atoms produced, or react with a halogen acceptor such as gelatin or sensitizers that reduce the atoms to halogen ions (see Figure 14-14).

Absorption of a quantum of light by the crystal excites an electron so that it is free to move through the lattice and may combine with an interstitial silver ion, thus yielding an atom of silver. This is most likely to occur at a nucleus produced by chemical sensitization, called a sensitivity center, which traps the electron and holds it until an interstitial silver ion arrives. There is a strong tendency for this atom of silver to give up an electron and thus return to the ionic state. It is also possible for the electron to recombine with the positively charged "hole" left when it was released from a halide ion. If exposure is sufficient, two silver atoms together form a sub-latent image that is not capable of development. However, a greater time will be required for the two atoms to give off electrons and return to the ionic state than is the case for a single atom. When sufficient exposure has been received to bring about four atoms of silver at the site, the grain may become developable. Further exposure of the grain to light adds to the number of silver atoms at the original site, and thus increases the developability of the grain. About 10 to 20% of the grains in a fast negative emulsion are rendered developable when four atoms of silver have been formed at the site, but the

average number of atoms required for developability is considerably higher.

The latent image is usually formed on the surface of the crystal, but a latent image can also be formed in the crystal's interior on exposure to light. This internal image is usually protected from the developer, but it can be developed in a solution containing a silver halide solvent. In nearly all emulsions the contribution of the internal latent image to the developed image is negligible. A grain with an internal image usually has a surface image. For purposes of experimental research, the surface image can be destroyed to demonstrate the existence of the internal latent image.

The positive holes, formed by the loss of electrons to form silver atoms, move to the crystal surface to neutralize halogen ions to atoms that are adsorbed by the gelatin. The gelatin in this context is referred to as a *halogen* or *bromine acceptor*.

While most of the latent image in ordinary photographic materials is formed on the surface of the crystal, the interior latent image plays an important part in some photographic effects. In the Gurney-Mott hypothesis the electron "traps" are considered to be distributed throughout the crystal but are more effective on the crystal's surface.

Photographic Effects

The mechanism of latent image formation is closely related to six photographic effects. These six are: *Reciprocity, Intermittency, Herschel, Clayden, Solarization, and Sabattier*. It is worth noting that these effects do not happen in digital photography. While film will suffer reciprocity, extended exposures in the digital world will increase noise in the image only. There are however many techniques that can be applied to the digital image to simulate these effect.

Reciprocity Effects

Photographic exposure is the amount of light falling on the emulsion (Exposure = Illuminance × Time). Reciprocal combinations of illumination and time will give the same exposure, but not necessarily the same density. This decrease in density with certain combinations of illuminance and time is called *reciprocity law failure* or *reciprocity effect*. When exposures are made at low light levels, the efficiency with which the sub-latent images are formed on the crystal is low because of the tendency of the silver atoms to give up an electron and return to the ionic state. Further exposure allows a greater number of silver atoms to accumulate around those few sub-images that survive, but these sub-images are relatively stable.

With long exposures at low light levels, silver atoms in the latent image can change back to silver ions.

When exposures are made at high illuminance, with correspondingly short exposure times, the electrons are released so rapidly that the relatively slower-moving silver ions cannot neutralize them fast enough for the centers to grow to the predicted size. A greater number of sub-image centers are spread over the crystal surface, and sometimes into the crystal's interior. There is more competition for the additional silver atoms formed, and thus a smaller number of them grow large enough to become permanent developable latent image centers.

Reciprocity law failure is caused by the relatively low efficiency of the formation of sub-image centers at low intensities with long exposure times and by the high efficiency of the formation of sub-image centers at high intensities, with corresponding wide distribution of competing sub-image

A series of intermittent exposures may not produce the same density as a single exposure even though the total amounts of light are the same.

centers. Emulsions for pictorial use are formulated so that the most efficient compromise between exposures made at low intensities and those made at high intensities generally occurs when the exposure times are in the vicinity of 1/10 to 1/100 second. The reciprocity law failure of an emulsion is the same for all wavelengths of light when compared on the basis of equal densities and equal times (see Figure 14-15).

The reciprocity law is valid for the production of electrons in the primary process of the Gurney-Mott theory (Figure 14-14), but does not apply to the secondary and other processes that are necessary for the production of the final image.

The reciprocity failure of a photographic material is dependent on the temperature of the material during exposure. Tests show that the failure virtually disappears at temperatures of −186° C, with an accompanying loss of sensitivity. Temperature variation has different effects on low- and high-intensity reciprocity law failure.

Exposures made with X-rays and gamma rays show no reciprocity failure, due to the high velocity of the electrons first liberated, releasing large numbers of electrons on collision with ions in the grain. Print-out papers also do not show reciprocity failure.

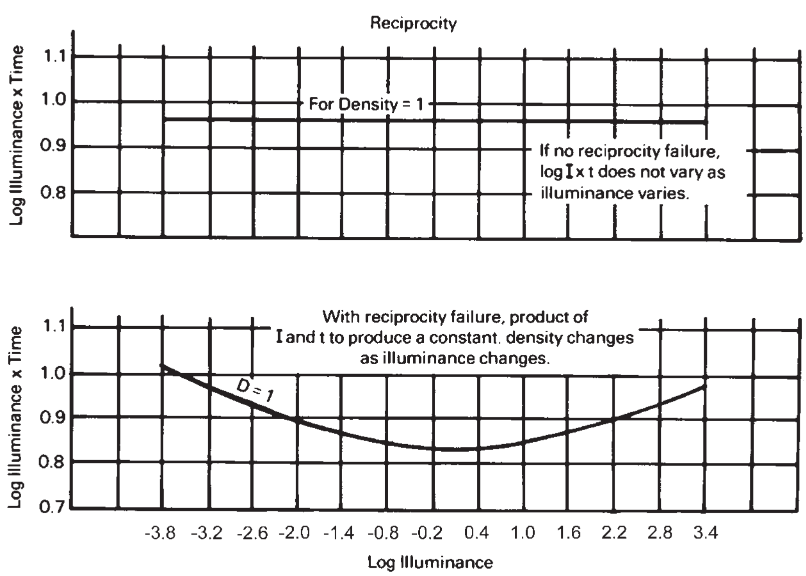


Figure 14-15 Reciprocity.

Intermittency Effect

The *intermittency effect* is closely associated with reciprocity failure. Intermittent exposure means exposures in discrete installments rather than in one continuous installment. If the intermittency rate is low, the intermittent exposure will produce the same photographic effect as a continuous exposure of equal total energy. As the frequency is increased at a given level of illumination, the photographic effect is decreased until with a further increase in frequency the loss in photographic effect becomes constant. The point at which this occurs is a critical value that varies with the illuminance level. If the intermittent exposure is made at a sufficiently high illuminance level, the photographic effect will be greater than that of a continuous exposure of equal energy. In relation to the U-shaped reciprocity-law-failure curve, the intermittency effect at the critical interruption frequency is equivalent to moving to the left on the curve. In the case of low illuminances on the left half of the curve, the move is upward, indicating that more exposure is required to produce a specified density. In the case of high illuminances on the right half of the curve, the move to the left is downward, indicating that less exposure is required to produce a specified density (see Figure 14-15).

Solarization

When a sensitometric curve is considered, *solarization* is the reversal or decrease in density with additional

exposure increase beyond that required to produce maximum density on the film (see Figure 14-16). The maximum solarization effect is produced with moderate developing times, while extended development reduces, or even eliminates, the effect. In addition, the presence of silver halide solvents, such as sodium thiosulfate and sodium sulfite, in the developer inhibits or removes the solarization. Developers that do not contain silver halide solvents usually produce the effect.

If halogen acceptors are present during exposure, solarization may be diminished or even eliminated. Thus, solarization is considered to be the result of rehalogenation of the photolytic silver formed at the sensitivity specks as the result of exposure. Normal exposure produces halogen at a rate that allows the halogen to react with acceptors such as gelatin. If the exposure is great, the production of the halogen proceeds at a rate beyond the capability of the acceptor, and thus may react with the latent-image silver to reform silver halide. This surface coating of silver halide, although it contains a latent image beneath it, will shield the latent image from the developer. This is sufficient to lower the number of developable crystals, and the result is a lower density. If the developer contains a silver halide solvent, it will remove the surface silver halide and thus expose the latent image for development.

With a solarized image, heavily exposed areas do not develop because rehalogenization produces a protective coating of silver halide on the latent images.

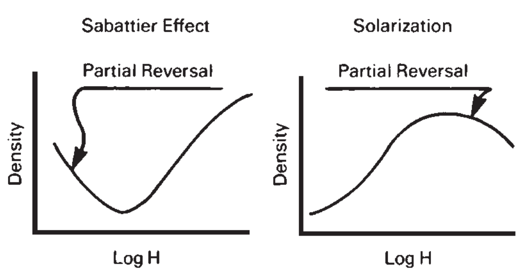


Figure 14-16 The Sabattier effect is the result of arrested development, wash, re-exposure, and further development. Solarization is the result of extended exposure and moderate development in a developer without silver halide solvents. Both effects produce a reversal image.

Sabattier Effect

The *Sabattier effect* is produced by developing an exposed photographic emulsion for a short time, washing it, and exposing the emulsion a second time. The film is then further developed, fixed, and washed (see Figure 14-16). The effect is sometimes confused with solarization, in that the final result is a partially reversed image. It appears to be caused by two mechanisms: (1) the image produced by the first development screens or acts as a negative and thus allows the exposure of the remaining silver halide to be modulated to produce a positive image during the second development, and (2) the by-products of the first development act as a restrainer in the developed areas. The migration of used and fresh developer across image boundaries may produce *Mackie lines*, a line of increased density just inside the denser area and a line of decreased density just inside the thinner area.

Latent Image Stability

The fact that amateur photographers sometimes allow months and even years to elapse between the time the first exposure is made on a roll of film and the time the film is processed attests to the stability of the latent image. Preservation has been exceptional in cases where exposed film has been frozen in ice, such as in the Arctic region, but images have been obtained with exposed film that has been stored for as long as 25 years under household conditions.

Latent images have produced usable images when development has been delayed for as long as twenty-five years.

These examples are not intended to suggest that the latent image is permanent and does not change with time. Since the latent image consists of a cluster of silver atoms, the loss of only a few atoms may render a silver halide grain undevelopable. An atom of silver can combine with an atom of bromine, for example, to form a molecule of silver bromide, reversing the effect of exposure. Images developed after long periods of time may have less contrast and be less distinct due to the spontaneous development of a larger number of unexposed silver halide grains. Delayed development of film increases fog. A point is reached where the developed latent image can no longer be detected. A small amount of development fog, however, can produce the effect of increasing the speed of the photographic emulsion and the density of the developed latent image in the same manner as *latensification* (see Figure 14-17).

For critical work, detectable changes in developed latent images sometimes occur in remarkably short times. Exposing a large number of black-and-white prints identically, and then developing part of the batch one day and the balance the following day, has been reported to produce a significant difference in density. Improvements in emulsion technology in recent years, however, has reduced the decay rate of the latent image in black-and-white printing papers.

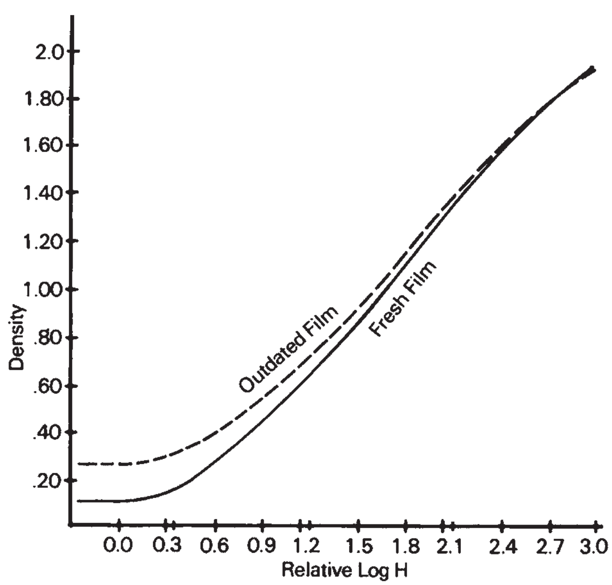


Figure 14-17 Effect of age on a typical black-and-white film.

Changes in the latent image of color printing papers are more serious because they can affect the color balance of the print in addition to the density and contrast. For this reason, recommendations are made to store color paper for a fixed time after exposure prior to processing to make the latent image change relatively constant. If the exposed paper is to be held for more than the hour or two normally built into the schedule, recommendations are that it be stored at 0° F (−18° C) or below, and then for a period of no more than seventy-two hours. Film manufacturers recommend that color films be processed as quickly as possible after exposure or that they be stored at a low temperature, noting that storage in a closed automobile on a hot day for only a few hours can have a serious effect on the developed image. They also warn against allowing color films to come into contact with various fumes, including those of chemical solvents and mothballs.

Some Alternative Systems

The familiar black-and-white and color films and papers that use gelatin as a suspension vehicle for the light-sensitive silver salts are but one of many ways to make a light-sensitive photographic system. Most of the older processes, such as *calotype, daguerreotype, cyanotype, albumen, wet collodion, ambrotype, carbon, carbro, gum bichromate,*

platinum, and *kallitype*, use something other than silver salts and/or gelatin. None has the light-amplification ability of silver and therefore they all have very slow speeds. The required long exposure times or high light levels limit their use in a camera, so they are relegated to photographic printing or certain types of recording where high sensitivity is not required.

Many of these older processes are also being rediscovered by photographers who are exploring their delicate tones and esthetic qualities. Some processes utilize silver and/or gelatin only in an intermediate step. Many of the present-day color processes are examples of the latter where the final images consist of dyes. Newer processes such as electrophotography and television use electrical and magnetic fields for image recording and reproduction. Light-sensitive microchips containing many light-sensitive picture elements have sufficient sensitivity to be used as disks in cameras.

Calotype Process

Another early process utilizing silver but not involving gelatin was the *calotype* process, invented by William Henry Fox Talbot, and patented in 1841. Talbot had obtained negative silver images on silver chloride paper as early as 1839, with what was later called the Talbotype process. The negative and positive images formed the basis of modern photography. Paper was sensitized with silver iodide, silver nitrate, and gallic acid, and was developed in gallic acid. This paper was used for both the camera negative, and for printing a positive from the negative.

According to a modern version of the process, the paper is first iodized by coating it with an approximately 7% solution of silver nitrate in distilled water, as shown in Figure 14-18. After the paper is dried it is floated on a solution containing about 7% potassium iodide and 1% sodium chloride, and dried again. It is then sensitized by flowing onto the surface a solution containing about 10% silver nitrate, 7% acetic acid, and 1% gallic acid, producing light-sensitive silver halide. The sensitized paper is dried and kept in the dark until ready for camera exposure. The exposed paper is developed in a solution containing about 0.8% gallic acid and 2.5% silver nitrate, producing a silver image. The developed negative is fixed in a solution of about 30% sodium thiosulfate (hypo) solution, washed, and dried. Prints can be made by exposing this negative on a conventional modern printing paper, or on another sheet of calotype paper.

History has seen many photographic systems other than the silver halide gelatin processes in use today—some of which still have significance.

The negative-positive calotype process, patented in 1841, used silver halide but did not use gelatin.

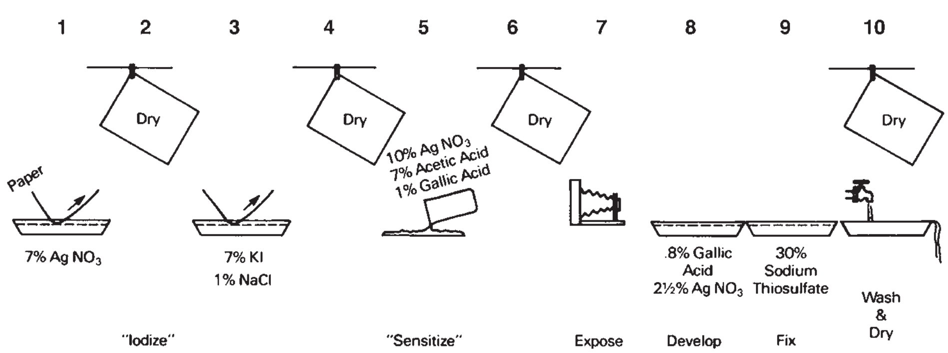


Figure 14-18 Calotype.

The daguerreotype process used a silver surface that was treated with iodine vapor to form a light-sensitive silver halide.

Daguerreotype

The process announced by Louis Jacques Mande Daguerre on August 19, 1839, introduced practical photography to the world. No gelatin was involved. A sheet of copper or brass was plated on one side with silver, which was buffed to a high mirror-like polish. It was then sensitized by placing it in a light-tight box containing iodine crystals, which gave off iodine vapor that reacted with the silver to form a coating of silver iodide. Exposures were made in a camera, and since the image was viewed on the surface of the plate and not through it, it was reversed from left to right, a condition that was corrected in practice by placing a mirror at 45° to the lens in front of the camera.

After exposure, the plate was placed in a box containing a dish of mercury that was heated to about 75° C (165° F). The mercury adhered only to the exposed parts of the plate, giving a whitish amalgam of silver and mercury. The plate was fixed in a solution of sodium thiosulfate (hypo), washed, and dried. When the daguerreotype was viewed so that the unexposed, undeveloped areas reflected the dark surroundings of a room, a positive image was seen. The photographic speed of the plate was increased by adding bromine to the iodine vapor, and the image strength could be improved by toning with gold chloride after fixing. Since the silver image was readily tarnished or damaged by handling, the plate was protected by placing it in a decorative cutout frame and covering it with glass.

The cyanotype process is a nonsilver printout process that requires only washing after exposure.

Cyanotype

The *cyanotype* (or blueprinting) process, invented by Sir John Herschel in 1842, is a nonsilver, nongelatin process. The ferric iron salt used in coating the paper is reduced by light to the ferrous state, which is then precipitated to Prussian Blue (ferric ferrocyanide, $Fe_4[Fe(CN)_6]_3$), by the action of the potassium ferrocyanide, the second component of the coating solution. The image is made up of varying densities of the Prussian Blue. A good grade of sized paper should be used. The paper is sensitized by coating, brushing, floating, or swabbing, with a solution consisting of about 12.5% ferric ammonium citrate and 7.5% potassium ferrocyanide (usually prepared by mixing separate solutions of these two compounds). Ferric ammonium oxalate can be substituted for the ferric ammonium citrate for increased speed, and about 1% of potassium dichromate can be added for increased contrast.

After exposure, a pale image can be seen, and processing normally consists of washing the prints in plain water to remove the unexposed soluble ferric salt, followed by drying. Prussian Blue is a fairly stable compound but it is soluble in alkalis, and the image is affected by impurities in the atmosphere that sometimes cause the image to take on a *metallic* luster in the denser areas. The cyanotype process can be used for printing continuous-tone photographs by contact from large negatives. It was also once used on a large scale for copying drawings from original tracings but has since been supplanted by the diazo process. (There are several other cyanotype formulas, but they all result in a Prussian Blue image.)

Cyanotypes can be converted to purplish-black images by bathing in a 10% sodium carbonate solution, which bleaches the image; then redeveloping in about 1% tannic acid solution. Cyanotype images can be inked over with waterproof ink, and the blue

bleached out with about 5% oxalic acid, followed by washing and drying, to produce a pen-and-ink drawing. A modification of the process (*pellet process*) produces a faint image that can be developed to a reversal image (positive to positive) upon development with potassium ferrocyanide. Another version, the *pointevin* process, is a positive-to-positive one that produces purplish-black lines on a light background.

Wet Collodion

The *wet collodion* process is a silver process, but it uses nitrocellulose as the binder for the halide crystals. It represents an important phase in the development of photography because it produces negative images on a transparent base, and was the principal method of making negatives from 1851, when it was introduced by Frederick Scott Archer, until the 1870s, when gelatin dry plates were introduced.

The cellulose nitrate is prepared by immersing cotton in a mixture of nitric and sulfuric acids, followed by washing in water. When dry, the nitrated cotton is dissolved in a mixture of ether and alcohol to produce collodion. (Prepared collodion can be obtained from chemical supply houses.) For photography, a small amount of sodium or potassium iodide or bromide is dissolved in the collodion. Some formulas have also made use of cadmium bromide and other halides. The prepared collodion is then flowed onto a clean glass plate until it is covered, and the excess collodion drained back into the bottle. The alcohol and ether evaporate and leave a tacky coating on the plate. Flow characteristics, which vary with atmospheric conditions, are adjusted by altering the relative amounts of ether and alcohol in the collodion. The tacky plate is immersed in the dark in a tank containing silver nitrate, about 65 grams per liter, for about 1 minute. The plate is then loaded into a special holder, while still wet, and inserted into the camera for exposure.

Following exposure the plate is developed before it has a chance to dry, by flowing a ferrous sulfate solution, or pyro solution, over the plate, and allowing the *puddle* to remain there during development. Some operators drain and replace the developer during development. However, it is thought that some physical development takes place, that is, some of the silver is plated back onto the image from the excess on the plate.

After development, the plates are fixed in a solution of potassium cyanide, or sodium cyanide, about 65 grams per liter, or with a sodium thiosulfate (hypo) fixing bath. The collodion image could be stripped off the glass to provide a film negative and a reusable glass plate, but this was not done often in the field. The wet collodion process continued to be used in the graphic arts industry until well into the twentieth century. The images were routinely stripped off the glass support, and recemented onto another support, or "flat"—a number of images placed together on a single support. The term *stripping* is still applied to the removal and repositioning of images into a new layout.

The wet collodion process was the first to produce a negative image on a transparent glass support, but the sensitized plate had to be exposed before it had time to dry.

Gum Bichromate

The *gum bichromate* process depends on the hardening effect produced by light on a bichromated colloid—in this case the colloid is gum arabic. Before the turn of the century the process enjoyed great popularity because of its adaptability to printing controls, and the wide choice of colored pigments

With the gum bichromate process, light produces a hardened image that remains after the unhardened gum is removed by washing.

With the xerographic process, light reduces the electrical charge in the exposed areas of a charged plate. The remaining charged areas attract a pigment that forms the final image.

Thermographic materials form images by reacting to heat radiation in any of several ways, including decomposition, softening, and the production of a transferrable image.

that could be used. While it is considered obsolete today, it is enjoying revived popularity as a means of artistic expression. There are various formulas for preparing the sensitizer, depending on the tonal rendering desired, but a fairly standard formula consists of mixing equal parts of a 10% solution of potassium bichromate with a 30% solution of gum arabic. The potassium bichromate can be dissolved in hot water, but the gum arabic requires soaking overnight or longer at room temperature. A small amount of thymol or other preservative can be added to improve the keeping qualities of the gum solution. Ammonium bichromate is sometimes used in place of the potassium salt to produce increased sensitivity. Any of a wide variety of water-miscible colorants can be added to the mixture.

The mixture should be applied to paper or another support, which is temporarily attached to stiff cardboard, using a brush. Experience will result in a technique that will produce a uniform coating. The coated material is dried in a dark room. Sensitivity is low until the material is nearly dry. The speed is similar to that of POP (printing-out-paper), but it is necessary to run an exposure test, as the speed depends on variations in the colorant.

The prints are made by contact, using sunlight, or some other source rich in actinic ultraviolet radiation, using a printing frame. A typical exposure is about 5 minutes. Development consists of dissolving the unhardened coating. The print is placed face-down in a tray of cold water for a time that may vary from 15 minutes to hours. The process can be speeded up with a gentle spray after the initial soaking. The image should not be touched until it is completely dry. During the drying stage, the print should be attached to a stiff support to prevent curling.

Electrophotography

There are many different *electrophotographic* processes (which use electricity to form images), some of which have not yet been fully developed. *Electrostatic* photography (xerography), which had its beginnings with the inventions of Chester Carlson in 1938, is now the most widely used electrophotographic system. The basic principle of image formation is that certain materials, such as selenium (early experiments were conducted with sulfur) and zinc oxide, will take on an electrical charge when passed near a source of high voltage, a corona charge. This is usually a positive charge in systems utilizing selenium, but the zinc oxide (in a resin binder) requires a negative charge. The action of light is to eliminate the charge, resulting in an image that can be made visible by dusting the plate with pigmented toner, which adheres to the charged (unexposed) areas. The toner also can be carried in a liquid.

With *xerography* (Xerography is a trade name, but xerography is now listed in dictionaries as a generic term), a drum plated or coated with selenium rotates first through an electric field (corona discharge) where it picks up a uniform positive electrical charge, as shown in planographic form in Figure 14-19. The image of the original is projected onto the charged drum, leaving an image consisting of positive ions in those areas that were not exposed. The drum is dusted with the toner, which adheres to the charged image. The drum then picks up a sheet of paper and both are passed through an electrical field that causes the toner to transfer from the

drum to the paper. The paper is passed through heat to fix the pigmented toner permanently to the paper. If the exposure is made while the drum is rotating, a scanning system is used to synchronize the image with the rotation of the drum, but an alternative system uses a stationary charged surface with electronic flash illumination.

Good line copies are readily made with these processes, but one problem in their development has been to produce good continuous-tone reproductions. There have been efforts in this direction to devise methods that control the corona charging rates, among other things, which are meeting with continued success. Since the toner can be made in various colors, and since successive images can be made on the same sheet, it is possible to produce multicolored copies. Positive images are produced, since the toner adheres to the areas that are not exposed to light.

Thermography

Thermography is another nonsilver, nongelatin process. Images are formed by heat, usually by radiation from an infrared lamp that is modulated by the image on the original document. The denser areas absorb infrared radiation and become hotter than the surrounding less-dense areas. The heat is transferred to the heat-sensitive material, which is placed in contact with the original. The most common changes are a physical softening in the heated areas, or a chemical decomposition. Since printing and typing inks generally do not strongly absorb infrared, it is necessary first to make an electrostatic copy of such originals and then make a thermographic copy from that copy—not a practical procedure if a single copy is needed.

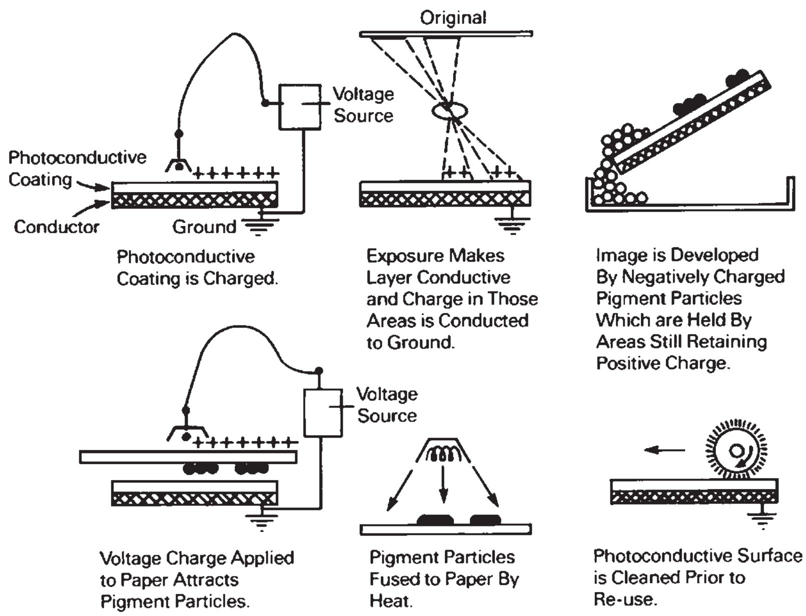


Figure 14-19 Electrophotography.

Diazo

With the diazo process, diazonium salts are decomposed by exposure to ultraviolet radiation and the remaining salts form a dye image when treated with ammonia.

The *diazo* family of nonsilver, nongelatin processes is mainly divided into two categories—one producing dye images, and the other vesicular images. With the dye image process, ultraviolet radiation decomposes compounds known as diazonium salts. The remaining salts are converted to azo dyes with ammonia or heat. The ammonia may be applied either in solution form or as ammonia fumes. Since dye is formed in the areas protected from radiation, a positive image is formed from a positive original. No fixing is needed because the sensitivity is destroyed in the non-image areas by the action of the exposing radiation.

A diazo material that produces black images on a white background is widely used for copying drawings, and the resulting prints are called white prints to distinguish them from blueprints. Diazo materials are available with paper, film, and foil bases and a wide variety of image colors. Limitations of the process are low

The image displayed on a television screen is produced by scanning a phosphor layer on the tube face with an electron beam, which causes the phosphors to emit light.

sensitivity and the need for an ultraviolet-rich source of radiation for exposure. The high-contrast characteristics of the sensitized materials make them unsuited for copying continuous-tone originals. However, they are capable of high resolution, and they were at one time considered favorable for reproduction of microfilm images and optical sound recordings.

With the *vesicular* process, crystalline and non-crystalline diazonium salts are randomly dispersed in a thermoplastic film (see Figure 14-20). Upon exposure to ultraviolet-rich radiation, the diazonium salt is decomposed and nitrogen gas is released into the thermoplastic film. Development consists of heating the film to change the light dispersal pattern mainly due to the tiny bubbles that are formed as the gas expands. Upon cooling, these larger bubbles remain and produce an image by scattering light (as contrasted to silver and dye images, which produce visible images by absorbing light). Fixation consists of a uniform exposure to radiation without heat which decomposes the residual diazonium compounds and the released nitrogen gas is allowed to diffuse from the film.

Although vesicular images appear low in contrast when viewed by diffuse illumination, the contrast is satisfactory when viewed by specular illumination. Since bubbles are formed where exposure occurs, a negative image is formed, but the processing procedure can be modified to produce a positive image. Typical applications are the production of positive images from microfilm negatives, black-and-white negatives from 35-mm color slides, and quick projectuals in audiovisual work. Before the displacement of black-and-white motion pictures with color, this process was a strong contender for making motion-picture release prints.

Electronic Image Display

There are multiple electronic processes that do not form permanent images, but when tied to a recording device such as digital video recorder produce images that can be modified and edited. Such devices include the cathode ray tube (CRT), rear projectors (RPTV), flat panel devices including liquid crystal and plasma displays, and

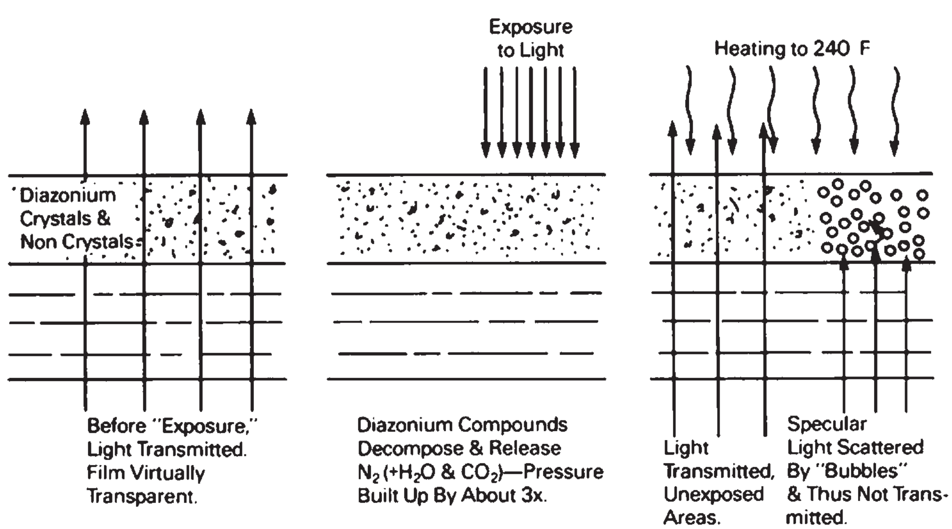


Figure 14-20 Vesicular film.

LED and organic light-emitting diode (OLED) technology.

The CRT is an evacuated glass tube that has a fluorescent screen and a electron gun. When the electrons from the electron gun strike the fluorescent screen light is emitted. The electron beam can be modulated to display images on the screen. CRTs are used in televisions, computer screens, radar screens and oscilloscopes.

A rear projector screen uses very bright lights and the principles of additive color to produce images. These are very popular for large home theaters.

The LCD or liquid crystal display is a thin flat display device that consists of an array of pixels in front of a light source or reflector. The LCD has a layer of molecules aligned between two transparent electrodes and two polarizing filters. The polarizing filters are aligned perpendicular to each other, which should block all light passing through. The electrodes apply an electrical field to the liquid crystals which align to control the amount light that passes through the system.

Plasma display panels are also flat, as LCDs are. Plasma displays have many tiny cells that are placed between two glass panels. Each cell contains an inert mixture of noble gases, typically neon and xenon. These cells are turned into plasma with an electrical current. The plasma then excites the phosphors to emit light.

The organic light-emitting diode (OLED) are a type of light-emitting diode. The emissive electroluminescent layer in an OLED is made of a film of organic compounds. The layer is typically a polymer substance that allows the organic compound to be deposited in rows and columns on a flat carrier. This produces addressable pixels. OLED can be used in televisions and computer displays. The advantage of this technology is that they do not require a backlight to operate and use less energy than an LED type display. They are also easier to manufacture than LCDs and plasma displays.

Charge-Coupled Devices

There are several ways in which images formed by light can be electronically recorded, including charge-coupled devices (CCD) and complementary metal-oxide semiconductor (CMOS) imagers. Many digital cameras and scanners exist that record images using these devices for later use as computer images.

CCDs serve as the light sensor in many contemporary still digital cameras and digital backs for view cameras and some medium-format hand-held cameras. The CCDs are made up of a large number of minute individual sensors arranged either in a single row (linear array) that scans the light image in the camera or in a two-dimensional format (area or block array), the same as film, that permits instantaneous exposure of the entire light image (for black-and-white pictures, or, with a mosaic of minute red, green, and blue filters over the sensors, for color pictures). The individual picture elements, called *pixels*, are sensitive to all wavelengths of light and ultraviolet radiation, like panchromatic black-and-white film and color film, and are also sensitive to invisible infrared radiation. Since sensitivity to ultraviolet and infrared radiation is not wanted for most images, it can be reduced or eliminated with appropriate filters on the surface of the CCD or elsewhere in the light path.

When exposed to the light image in the camera, each pixel produces an electrical charge that is proportional to the illumination level. The light image

formed on the surface of the CCD by the camera lens is in analog form, as with film, but since computers require the information to be in digital form the CCD is designed to move the individual pixel charges in sequence through an analog-to-digital-converter (ADC). The variations of voltage of the individual CCD pixels, which represent variations of image illumination, are converted to a sequence of 0s and 1s for each pixel by the ADC, the length of the sequence of 0s and 1s being determined by the bit depth of the CCD. An 8-bit-depth system, for example, would produce strings of eight 0s and 1s, which would represent 28 or 256 tones from black to white.

With the diffusion transfer process, the silver halides that remain after development of a negative image are used to form a positive image.

Dye Transfer

The gelatin-silver emulsion provides an intermediate matrix from which the image is produced by transferring dye to a mordanted gelatin-coated film or paper support. (A mordant is a substance that binds a dye to a given material, in this case, gelatin.) With the Technicolor motion picture process, now defunct in the United States, a set of matrices (one each dyed with cyan, magenta, and yellow to represent the red, green, and blue records of the scene) transferred the dyed images to a gelatin coated *imbibition blank film*. Beginning in the 1930s the images were transferred to a processed positive film carrying the silver sound track. For dye transfer prints on paper, see Figure 14-21.

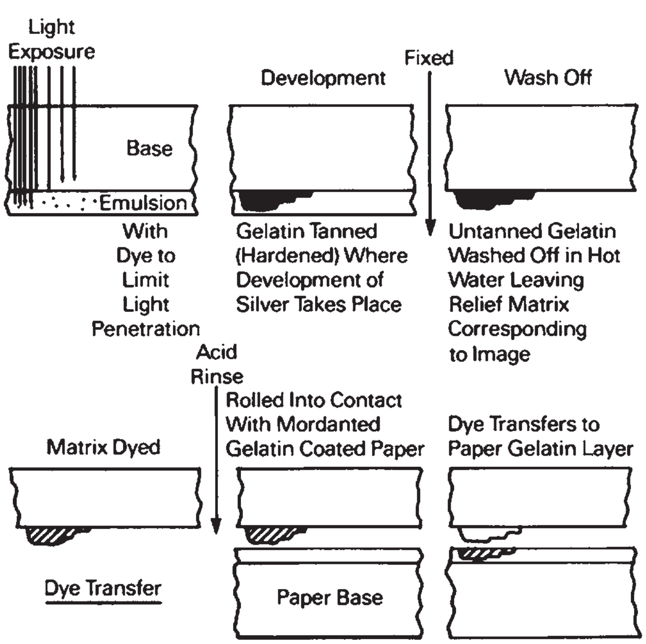


Figure 14-21 Dye transfer.

Diffusion Transfer

With *diffusion transfer*, an exposed gelatin-silver negative emulsion on either a film or paper base is brought into contact with a receiver sheet, with a viscous activator solution containing a strong alkali and a silver halide solvent such as thiosulfate placed between them. The negative emulsion also contains a developing agent, and the receiver sheet, which is not light sensitive, contains nucleating particles such as silver sulfide, along with a developing agent. The activator causes development to take place in the negative, and the halide is reduced to silver to form a negative. At the same time, the undeveloped silver halide in the negative is dissolved by the thiosulfate, and diffuses to the receiving sheet. The silver sulfide particles serve as nuclei for development of the halide that diffuses to the receiving sheet, and it is reduced by the developing agent, now activated, to metallic silver to form a positive image. When the two sheets are separated, the remaining viscous activator—developing/solvent solution—stays with the negative, leaving the clean positive image on the receiving sheet. No further fixing or washing is required. The process normally goes to completion, although varying the time and/or temperature can permit some variation in density or contrast.

REVIEW QUESTIONS

1. The major disadvantage of cellulose nitrate as a support was that it . . .

   A. was expensive
   B. became brittle
   C. turned opalescent
   D. was combustible
   E. had a disagreeable odor

2. A disadvantage of polyester as a photographic emulsion support for motion-picture film is that it . . .

   A. is difficult to perforate for sprocket holes
   B. acts as a light pipe
   C. has a strong inherent color
   D. tears easily
   E. curls excessively

3. NC coatings on photographic films are applied to the . . .

   A. base side
   B. emulsion side
   C. edges

4. The name of non-RC photographic papers could be abbreviated . . .

   A. RF
   B. FC
   C. FB
   D. FF

5. Brighteners are used in . . .

   A. negative black-and-white films
   B. negative color films
   C. reversal color films
   D. black-and-white infrared films
   E. photographic papers

6. The number of groups of photographic paper thicknesses listed in the American National Standard on paper thicknesses is . . .

   A. 3
   B. 4
   C. 8
   D. 7
   E. 9

7. A statement that is not true for photographic gelatin is that gelatin . . .

   A. can be changed between liquid and solid states by changing the temperature
   B. has no effect on the sensitivity of the emulsion
   C. permits penetration by liquids
   D. serves as a receptor for silver ions in latent image formation
   E. is transparent

8. The more uniform the silver halide grains are in size in an emulsion, the . . .

   A. higher the contrast
   B. lower the contrast
   C. higher the speed
   D. lower the speed

9. The inherent spectral sensitivity of silver bromide is to . . .

   A. ultraviolet, blue, green, red, and infrared radiation
   B. ultraviolet, blue, green, and red radiation
   C. ultraviolet, blue, and green radiation
   D. ultraviolet and blue radiation
   E. blue radiation

10. If the gelatin is omitted during the precipitation stage of emulsion making . . .

    A. the chemicals will not react
    B. the silver halide formed will decompose rapidly
    C. the silver halide will not stay in suspension
    D. the silver halide formed will rapidly dissolve

11. Sensitizing dyes increase sensitivity of photographic emulsions to wavelengths of radiation . . .

    A. reflected by the dye
    B. absorbed by the dye
    C. transmitted by the dye

12. When exposed but undeveloped film is placed in a sodium thiosulfate solution, the latent image is . . .

    A. unaffected
    B. destroyed
    C. converted to a visible image

13. At the end of the primary process of latent image formation, the sensitivity center . . .

    A. has a positive electrical charge
    B. has a negative electrical charge
    C. is neutral

14. Movement during the secondary process of latent image formation consists of movement of . . .

A. electrons
B. sensitivity specks
C. positive ions
D. negative ions
E. all of the above

15. The minimum number of atoms of silver required to be formed during exposure for a silver halide grain to be developable is considered to be . . .

A. one
B. two
C. three
D. four
E. five

16. A common characteristic of cyanotype, gum bichromate, and other nonsilver processes is that . . .

A. none is capable of producing a neutral color image
B. none of the images formed has as good archival permanence as silver images
C. all are more expensive than silver processes
D. all have lower film speeds than silver processes
E. none is capable of producing an image of normal contrast

17. The first negative-positive photographic process is considered to be the . . .

A. daguerreotype process
B. cyanotype process
C. calotype process
D. gum bichromate process
E. electrostatic process

18. An example of a photographic process that does not use silver is the . . .

A. daguerreotype process
B. cyanotype process
C. wet collodion process
D. printing-out-paper process

19. The distinctive characteristic of the wet collodion process at the time it was introduced was that it was the first . . .

A. negative-positive process
B. silver-halide process
C. process to use dyes
D. process to use liquid development
E. process to use a transparent base

20. A photographic process that is based on the hardening effect of exposure to light is the . . .

A. cyanotype process
B. thermography process
C. electrostatic photography process
D. gum bichromate process
E. diazo process

21. In electrostatic photographic processes, light forms a latent image by. . .

A. placing an electrical charge on a surface
B. neutralizing an electrical charge on a surface
C. hardening toner on a supporting surface
D. creating a fluorescent image on the receiving surface

22. A distinguishing characteristic of the diazo dye process is that the images . . .

A. have low contrast
B. have high contrast
C. have a magenta color
D. are composed of silver dyes
E. are fixed with ammonia gas

chapter

15 Black-and-White Photographic Development

"Self-Portrait" by Robert Lussen, Advertising Photography student, Rochester Institute of Technology.

Negative Development

When a silver halide emulsion on film or paper has been exposed to a light, a latent image is formed in the emulsion and in most circumstances this image would not be visible because of the small amount of silver produced. The energy required to produce such a latent image is relatively small, permitting exposure

Development amplifies the latent image by a factor of up to a billion times.

times of 1/20,000 second or shorter under daylight illumination. The development process amplifies this image by a factor of up to 10^9 or a billion times producing the final silver image. Assuming that optical density is approximately proportional to the amount of silver per unit area of the image, it is possible to calculate the density of a latent image. For example, the maximum density that can be obtained in a reflection print is about 2.0. This density divided by 10^9, the maximum development amplification factor, equals 0.000000002, the calculated density of the corresponding latent image. The smallest density difference that can be measured with conventional densitometers is 0.01.

The subsequent fixing step converts the unexposed, undeveloped silver halide remaining in the film to soluble silver complexes that are washed away to leave only the silver image. The photographic process is a negative-working one, in that dark areas in the scene record as light areas on the film, and light areas record as dark on the film. In the case of the original camera exposure, a negative image is created that serves as a light modulator to produce a positive image on another piece of sensitized material for viewing.

Direct-Positive Images

A positive image can be produced on some types of emulsions by overexposing them to such an extent that the reversal region of the characteristic curve is reached (see Figure 15-1). X-ray film, for example, could be used as a contact-printing medium for reproduction of an original negative X-ray image as a negative image simply by grossly overexposing it, and processing in the usual way. Emulsions have been produced that give positive images with normal development for copying and duplicating negatives.

Reversal Processing

The basic negative-working silver halide emulsion system can be used to produce positive images by means of reversal processing (see Figure 15-2). Some emulsions are more suited to this type of processing than are others. Reversal processing begins with a negative image, as in normal processing after developing but before fixing. The silver image is then removed in a bleach, such as potassium permanganate, which reacts with the metallic silver to form soluble silver ions that

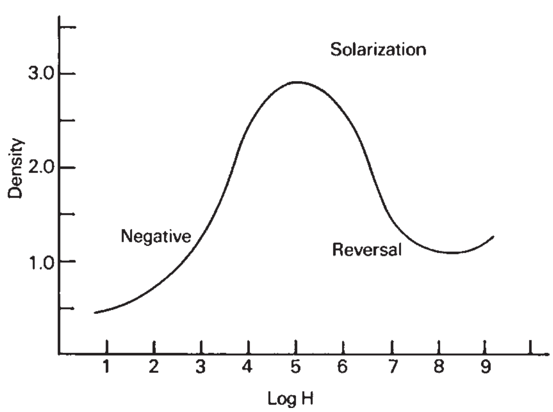


Figure 15-1 Solarization.

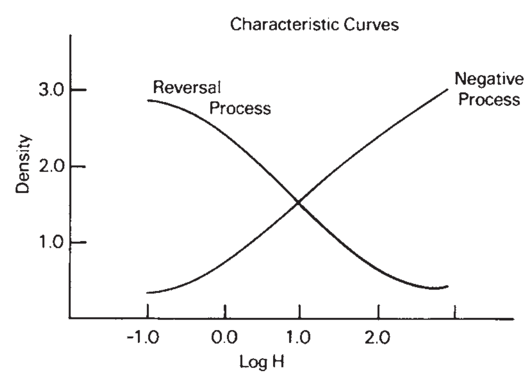


Figure 15-2 Densities increase as exposure increases in a negative process while densities decrease with increased exposure in a reversal process.

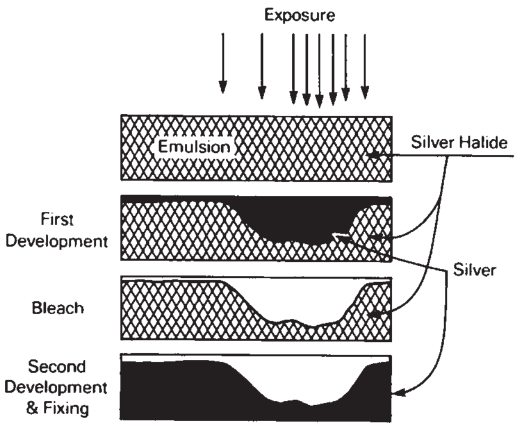


Figure 15-3 Reversal process.

are washed away, leaving the undeveloped silver halide in the emulsion. The remaining silver halide is then exposed to a strong light source, and developed again to produce a *reversed* or positive image. The regions that do not receive much original image exposure have very little density after the first development, but a great deal of halide is available to the second developer to produce a high density. Similarly, where there was high exposure in the beginning, there is little silver halide remaining for the second exposure and development, and low density is produced, as shown in Figure 15-3.

More recently, fogging developers have been used for the second or reversal development, which eliminates the need for second exposure.

Mechanism of Development

Latent images can be divided into surface latent images and internal latent images. Most of the development takes place with the surface latent image, and the internal latent image normally contributes little to the total image. The latent image is formed when a certain number of photons have produced a nucleus of silver atoms in or on the surface of a silver halide grain. Four atoms of silver are considered to be the minimum number that constitutes a latent image.

Development is the selective reduction to silver of additional silver halide molecules around the site of the silver latent image nuclei, with no appreciable reduction in those areas that have not been exposed to light. As development continues, the amount of metallic silver grows, and if carried far enough the entire silver halide grain is converted to metallic silver. There are basically two types of development—chemical development and physical development. In physical development, the silver is provided by a silver salt in the developing solution, whereas in chemical development the silver comes from the reduction of silver halide grains in the emulsion. In most instances, some physical development takes place along with chemical development as a result of the silver provided by the solvent action of sodium sulfite on silver halide grains, and the amount varies with the type of developer. Physical development can be accomplished after fixing the exposed but undeveloped image, in which case the silver nuclei not removed by fixing serve as the focal points for accumulation of silver from the developer, which contains a soluble silver compound. The acid in conventional fixing baths will destroy the latent image, however.

Some physical development usually occurs with so-called chemical development.

Most developers contain a reducing agent, an alkali, a preservative, and a restrainer.

Constitution of Typical Developers

The most important ingredient in a chemical developer is the *developing agent* or chemical reducer agent that converts the exposed silver halide to metallic silver. Most developing agents require a pH higher than 7 to function,

Developing agents provide electrons to reduce silver ions to silver atoms.

and for this reason the developer also contains an *alkali*, also called a base. In order to minimize oxidation of the developing agent by oxygen in the air, the solution also usually contains a *preservative*, most often a sulfite salt. A *restrainer*, usually a bromide salt, is also part of most developers. The restrainer has the effect of slowing the rate of development, but this effect is greater in the unexposed areas than in the exposed areas of the emulsion, thereby limiting spontaneous development, or chemical fog. The presence of a restrainer in the developer formula also tends to minimize variations due to the release of halide ions during development, which would themselves act as restrainers (see Figure 15-4). Bromides or other halides are also sometimes referred to as anti-foggants, but this term is usually applied to a number of organic compounds that are used at much lower concentrations than bromide.

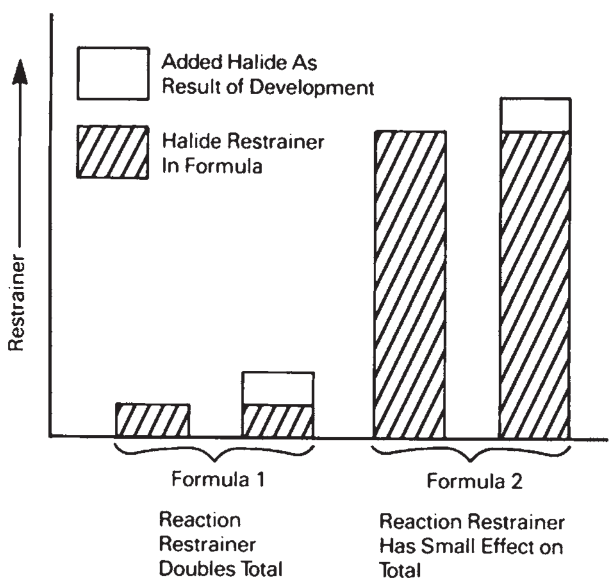


Figure 15-4 The restraining effect of reaction products of development is much greater when the developer formula contains a low amount of restrainer. A larger amount of restrainer in the developer formula makes the developer more tolerant of increases in restrainer because of the by-products of development.

A developer formula may also include other compounds that accelerate development, provide more even development, prevent the formation of insoluble compounds, etc.

Developing Agents

Common developers today make use of organic developing agents, although in the past inorganic metallic agents such as ferrous sulfate have been used. Development takes place as a result of the transfer of an electron to the silver halide. With ferrous sulfate, the iron of the developing agent goes to a higher valence in the presence of an organic ion such as oxalate. (The loss of an electron to Ag^{+} converts Fe^{++} to Fe^{+++}.)

$$Fe^{++} + Ag^{+} \rightarrow Ag^{0} + Fe^{+++}.$$

Ferrous sulfate developers were most commonly acid with a pH range of 4 to 6, but they can operate in an alkaline solution.

Hydroquinone

The majority of black and white developers utilize *hydroquinone* and *Metol* as their developing agents. Hydroquinone, discovered in 1881 by Abney, is probably used more than any other developing agent although usually in combination with another developing agent. It requires strongly alkaline solutions, since it has relatively low energy. Hydroquinone is slow to take effect but, once it has started, proceeds to develop rapidly and produces high contrast. It is quite sensitive to changes in temperature, and is practically inactive at temperatures below 15° C (59° F). In strongly alkaline solutions, it is a good developer for high-contrast and line copy work. Developers made with hydroquinone tend to produce

stain and fog unless sufficient sulfite and bromide are included in the formula. Both hydroquinone and pyrogallol tan the gelatin of an emulsion adjacent to those areas where development takes place; and either of these developing agents, or a combination of both (sometimes with other agents), is used in tanning developers. Tanning developers are used to produce matrices that can be dyed, with the dye being transferred to a mordanted paper or film as in the dye transfer or, previously, the Technicolor motion-picture film processes.

Metol

Metol, introduced by Hauff about 10 years after the discovery of hydroquinone, is another popular developing agent. It is packaged, sometimes with a modification of acidic counter-ion, under a variety of proprietary names other than Metol—such as Elon, Pistol, and Photol. Metol is unlike hydroquinone in its developing action. It is a soft-working developer, development is initiated almost from the start of the developing time, it retains much detail in the images produced, it is not very sensitive to restrainers such as bromide, it has good shelf life, and it is capable of developing relatively large quantities of photographic emulsion before becoming exhausted.

MQ Developers

Developer formulas made with both *Metol* and *hydroquinone* (MQ) produce an effect superior to either one used alone or the sum of the two used separately. This super-additive effect seems to have the advantage of an earlier induction period, allowing the hydroquinone to come into play sooner than it otherwise would. The super-additivity, however, exists not only during the induction period, but also at any degree of development. One explanation is that Metol is the primary developing agent and its oxidation product is reduced back to Metol by the hydroquinone as long as any hydroquinone exists in the developer solution. Several other developer combinations also produce an improved working characteristic, but Metol and hydroquinone are the best known. Phenidone and hydroquinone used together produce a similar super-additivity effect.

Accelerators

In order for the developing agent to function properly, the pH of the solution must be stable and alkaline, usually around the pH range 8 to 12 for with organic developing agents. This is accomplished by adding an alkaline buffer, or a mixture of compounds designed to maintain the pH at the desired level over the life of the developer, or at least during the development time of a given film. Sodium hydroxide is a strong alkali that is used for some types of developers, but the amount required to produce the required pH for most developers would be small, and the hydrogen ions liberated during development would rapidly change the pH. If the required pH is above 12 or 13, however, the quantity would be sufficient to maintain the pH even after the hydrogen has neutralized a substantial proportion of the hydroxyl OH^- ions to H_2O.

Most developers require that the alkali be buffered so as to maintain the availability of OH^- ions over a period of use. The buffering compound is usually a salt of a weak acid, such as sodium phosphate, sodium metaborate, sodium sulfite, or sodium bicarbonate. Several factors, including other chemicals in the formula, affect the

Metol and hydroquinone used together in a developer develop more silver than the sum of the silver produced by the two used separately.

The activity of most developers increases as the pH is increased by adding alkali.

Without a restrainer, most developers would develop an excessive number of the unexposed silver halide grains.

pH of the developer but the choice of alkali is the most significant one. The pH, then, is an indicator of the relative activity of the developer; the higher the pH, the higher the activity. Some types of developing agents require a strong activator to make them function, whereas others can function with relatively weak activators, and a few with none at all. The following typical accelerators are arranged in order of decreasing alkalinity:

Sodium hydroxide, pH	12+
Sodium carbonate, pH	11.5
Sodium metaborate (Kodalk), pH	10.8
Borax, pH	9.6
Sodium sulfite	(weak alkali)

Preservatives

Being a reducing agent, the developer will also react with oxygen in the air and thus lose its capability to develop a silver image. A *preservative* is added to the solution to prevent aerial oxidation. Sodium sulfite is the most commonly used preservative for developers utilizing organic developing agents. In the case of Metol-hydroquinone developers, the sulfite also serves the purpose of removing the reaction products of regeneration of the Metol by hydroquinone, so that the process can go on without slowing down. Sulfite also acts as a weak silver halide solvent, forming complexes that provide for a degree of physical development—the effect being influenced by other ingredients in the formula such as bromide, certain developing agents, etc. A small amount of physical development contributes to "fine-grain" development. In color developers, where the formation of dyes requires further reactions with oxidation products, the amount of sulfite must be kept to a minimum to prevent removal of the intermediate reaction products.

Restrainers

A simple developer formula (developing agent, activator, and preservative) may not differentiate adequately between the exposed and unexposed grains of silver halide in the emulsion. That is, in addition to developing the image grain, it may also tend to develop the non-image grains to produce silver or fog. (Restrainers sometimes cause some reduction in emulsion speed, especially if used in larger amounts.) A soluble halide, usually bromide, is added to the solution to act as a restrainer. It has the effect of controlling the reduction process so that there is a better differentiation between exposed and unexposed grains. In addition, since one of the reactions of development is the release of bromide or other halide into the solution, these ions will act as a restrainer. As more and more film is processed in the developer, additional halide will be added to the solution, thus increasing the restraining effect. A quantity of bromide in the developer formula minimizes the variability produced by the addition of relatively much smaller quantities of halide resulting from development (see Figure 15-4).

In the processing of multilayer color films where at least three emulsions have to be quite precisely controlled relative to one another, the maintenance of the halogen ions in the developer may have to be closely monitored. The restraining action of various halides is considerably different—iodide, for example, requiring one-thousandth the quantity of bromide required to produce a given

restraining action. On the other hand, the amount of chloride required is so high that it is not useful as a restraining agent.

Anti-Foggants

Anti-foggants are halides such as potassium bromide that restrain the development of fog in non-image areas during development. However, the term is usually reserved for another class of developer additives that minimize fog, usually with less effect on the overall speed of the emulsion. The term is applied to a group of organic compounds sometimes used in the preparation of emulsions, as well as developers, although the specific compounds are not necessarily interchangeable in the two applications. Some high-energy developers that require a high pH, for example, must of necessity incorporate an anti-foggant of this type to keep the fog at an acceptable level. Since the organic anti-foggants usually require lower concentrations than does bromide, they may be used where high concentrations of bromide are out of the question because of its effect on the other characteristics of the emulsion. Typical anti-foggants used in developers include 6-nitrobenzimidazole and benzotriazole.

Other Development Accelerators

Numerous compounds increase the rate of development when added to developer formulas due to effects other than the effect of the pH increase produced by the developer accelerator. These compounds work in a variety of ways. Some wetting agents, for example, have a positive charge (cationic), and decrease the induction period by canceling out the negative charge on the silver grain. Some sensitizing dyes with positive charges can have a similar effect. Certain neutral salts such as potassium nitrate and sodium sulfate also have an accelerating effect, which is thought to be caused by the improved diffusion of the developer ions through the gelatin of the emulsion. Another class of compounds that are weak silver solvents also act as development accelerators through the extra density provided by physical development (e.g., sodium thiocyanate). Wetting agents are sometimes added also for the purpose of smoothing out the flow of developer over the emulsion surface to produce more uniform development.

The concentration of developer solutions has a positive but not always predictable effect on the rate of development.

Other substances, manufactured under proprietary names, are often added to developer formulas to increase shelf life, lower the freezing temperature of liquid developers, improve mixing and solution capabilities, etc. Thus a packaged formula may be considerably different from a mixed formula used for the same purpose, or sometimes even have the same name. These proprietary formulations often provide competitive advantages in handling, and they are not disclosed to the general public.

Concentration of Developer

The components of a developer interact in a variety of ways. The developing-agent concentration, the alkali and resulting pH, the restrainers, and the sulfite or preservative concentration influences the development rate. The interaction of all these components is not constant, and adds further to the complexity. For example, it is often dif-

ficult to predict the results of dilution of many developer formulas. Some of them are designed to minimize these interrelating effects, and carry recommendations for diluting to various strengths to meet specific photographic requirements. In general, these developers are such that the product of dilution and development time to provide a given degree of development is not always constant, and each dilution should be tested with the type of film being used. Many developer formulas are such that a concentrated stock solution is prepared, which is diluted to various strengths as required.

Other factors affecting the degree of development are time, temperature, and agitation. These are interrelated so that a change in one can, to a considerable degree, be compensated for by a change in the other. Thus, different developing times are recommended for tray development of film with constant agitation and tank development with intermittent agitation. Agitation should be selected to produce uniform development over the picture area, not to control the degree of development. Most photographic processes, however, are designed to function best at a prescribed combination of time, temperature, and agitation. This is particularly important for color processes, where the relationship of reproduction characteristics between the red, green, and blue records has to be precisely maintained.

The temperature coefficient is the development time factor that compensates for a decrease in the temperature of 10°C.

Development Time

The chemical effects of development are not constant throughout the total time of the process. In the beginning there are no reaction products, and the developer has to penetrate the emulsion to gain access to the silver halide grains. As soon as the development process starts, reaction products begin to form and a restraining action comes into play, which is controlled to some extent by the removal of these products and their replacement with fresh developer by means of agitation. In the beginning there is also a relatively low concentration of silver ions present as the result of the solvent action of the developer, and it is some time before any physical development begins to take place. Rapid-acting developers, therefore, have a minimum of physical development components, whereas developers requiring extended times tend to have greater physical development components. Most fine-grain developers require relatively long developing times. The composition of the developer, the proportions of the developing agents, etc., have significant effects on the development characteristics with time. Most developer formulas in common use have been optimized for performance throughout the range of times that produce the desired contrast indexes for films.

Developer Temperature

Development time is also a function of developer temperature. But again, there is no hard and fast rule for quantifying the relationship that would apply to all developer formulas. In practical situations with well-designed developers, and within the range encountered in normal practice, the rate of development approximately doubles for every 10°C (18°F) increase in temperature. The *temperature coefficient* is the ratio of the increase in development time that occurs when the temperature is decreased by 10°C (18°F). It can be determined by observing the times for first appearance of the image in the developer at the two different temper-

atures and applying the following formula (Eq. 15-1):

$$\text{Temperature coefficient} = T1/T2 \quad \text{(Eq. 15-1)}$$

When the developer contains two developing agents, the coefficient is useful over only a limited range. Some typical coefficients are:

Metol	1.3
Pyrogallol	1.9
Hydroquinone	2.5
Metol-hydroquinone	1.9

If the time to achieve a constant gamma at two temperatures is plotted on a graph in which the time scale is a ratio scale, a chart is produced that will show the time of development for any temperature required to produce the gamma, as shown in Figure 15-5.

Developers with hydroquinone as a developing agent have a relatively high response to changes in temperature, whereas those with Metol or Phenidone have a lower response. With the combination of Metol and hydroquinone this is evened out to some extent, but at lower temperatures there is less developing effect of the hydroquinone than Metol, and at higher temperatures the reverse is true. The concentration of bromide in the developer affects its response to temperature variations, as does pH. A higher pH value or a lower bromide concentration makes the developer less responsive to temperature variation (it has a lower temperature coefficient).

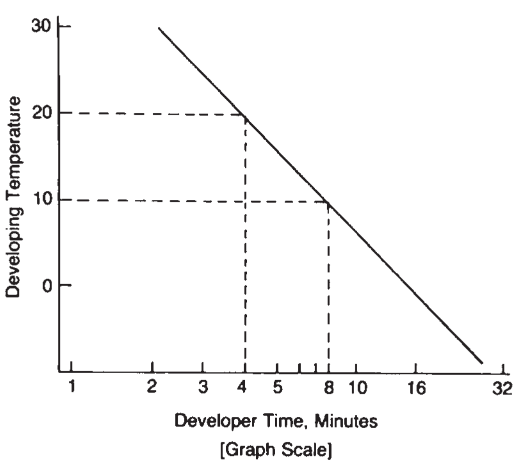


Figure 15-5 Time-temperature graph.

Developer Agitation

Agitation removes used developer from the surface of the emulsion and replaces it with fresh solution.

Agitation affects both the degree and the uniformity of development. When development starts, the solution penetrates into the emulsion to react with the silver halide grains. As this proceeds, the developer is used up, and has to be replaced with fresh developer. The presence of the gelatin retards the diffusion, but in time the partially exhausted developer diffuses to the surface of the emulsion. If development is stagnant, this exhausted developer accumulates at the surface and slows down development. Agitation of the developer removes the exhausted developer and replaces it with fresh solution that diffuses into the emulsion to continue the development process. Agitation rate should be geared to obtain maximum uniformity of development. With high-acutance developers, where the image enhancement is achieved by the accumulation of exhausted developer and of fresh developer, at the edges of high densities and low densities, respectively, little or no agitation is recommended. With short developing times, agitation has a greater effect on degree of development and overall density than it does with long developing times.

To ensure uniformity of development, the manner of agitation is important. There should be a nonlinear flow of the developer over the

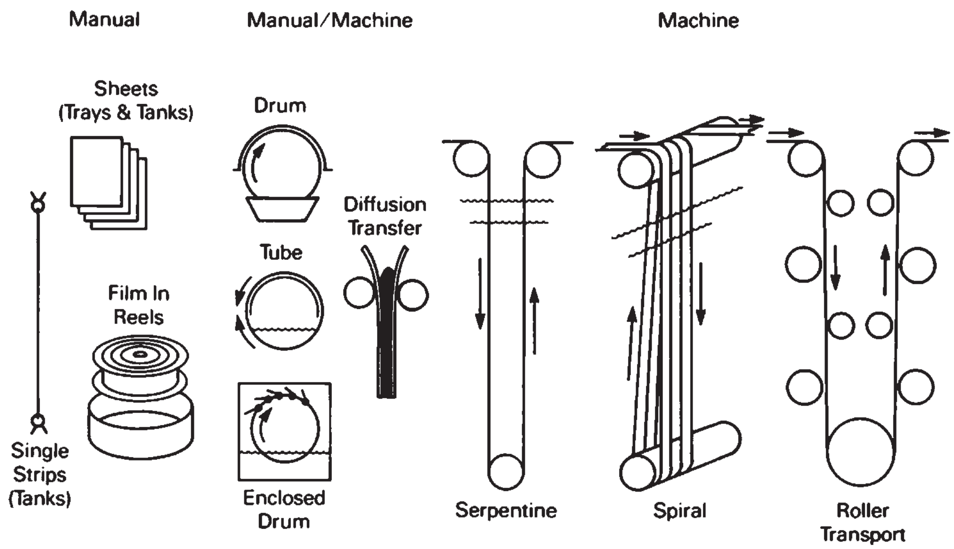


Figure 15-6 Some film and paper processing configurations.

film; otherwise large areas of density differing from the surrounding area will allow exhausted (or relatively fresh) developer to be swept across adjacent areas of differing exposure. A motion-picture film, for example, that is carried through the process in a linear fashion will show *drag*, areas of light density trailing dark areas on the film. The effect would be more prominent with short developing times. Likewise, intermittent agitation in trays can produce standing waves that will cause patterns on the developed film. Constant gas-burst agitation will tend to produce linear patterns, but if the bursts are intermittent, the combination of the bubbles' sweeping action followed by a period of stagnation will produce a more uniform result on the developed film. With tray processing constant agitation is recommended, but the tray or the materials in it should be moved in a random way (the tray is rocked, first one corner down, then the second) so as to minimize standing waves or directional effects.

The type of processing apparatus used has a strong influence on the degree of agitation (see Figure 15-6). Deep tanks in which the film is manipulated by hand can produce minimum agitation, as well as can stagnant tray development. Shallow tanks, spiral reels, and trays offer an intermediate degree of agitation and require well-defined agitation techniques to minimize non-uniformity problems. Processing drums, on which the film or paper is held in close proximity to the rotating drum surface with the developer carried between the drum surface and the emulsion surface, produces close to maximum agitation—the developer is exchanged at a very high rate. The roller transport processor produces a similar high degree of agitation. Tubes that carry the sensitized material inside, with the developer and other solutions flowing over the emulsion as the result of rotating or tilting the tube, also produce a high degree of agitation. Processing machines for long lengths like motion picture films with spiral configurations also provide good agitation, but these can lead to unevenness because of the linear passage of the film through the solution. Here, extra agitation of the solution by means of circulating

pumps and jets can be made to sweep the film to minimize these problems.

Replenishment

When processing small volumes of photographic materials, it is best to use the developer once and to then discard it. In this way uniform fresh developer is always used, and the resulting development is more uniform from one time to the next.

When larger quantities of materials are being processed, it is not economical to discard the relatively large volumes of solutions required, and so replenishment can maintain the constant activity of the developer (or other solutions used in the photographic process). In determining the makeup of the replenisher formula and the rate of addition, several factors have to be considered. These include: (1) the loss of developer resulting from carry-out by the film or paper as it is removed from the solution, (2) loss in developer activity caused by accumulation of reaction products of development in the solution, mainly soluble bromide, and to some extent other halides, (3) loss of activity casued by exhaustion of developing agent and sulfite consumed in the developing process, (4) increase in developer concentration caused by evaporation, and sometimes (5) carry-in of water or other chemicals if a pre-bath or pre-rinse is used prior to development. (Other steps in a process will also have to take into account the carry-over of the previous solution or rinse.)

The replenishment formula is calculated to accommodate these changes caused by processing, and to maintain the activity of the developer at a constant level. Such a formula is established by measuring the changes in the developer's chemical composition as measured quantities of film or paper are processed, calculating the amount of each chemical required to maintain the developer at its original strength, and adjusting this formula by actual performance tests. Because there are differences in the variables, it is often necessary to adjust the replenishment rate and/or formulation, especially if the process is to be maintained over a long period of time.

Developer replenishers are designed to maintain a constant level of activity in developers used to process large amounts of film or paper.

Some moderate volume replenishment systems are designed to be replenished over a period that would require the addition of an amount of replenisher equal to the volume of the original developer solution. Then the developer is discarded, and a new developer, along with an equal volume of replenisher, is prepared for use with additional films. This generally avoids or minimizes the problems that can arise when attempting to maintain the process over a long period without re-mixing. With some systems, only a replenisher chemistry set is sold, and a starter solution is provided that adjusts the replenisher to make it similar to a *seasoned* developer by adding bromide and reducing pH with an acid, and without processing any film to *condition* the developer. This becomes the properly compounded developer, and the replenisher itself is used for replenishment as intended.

Replenisher formulas generally supply additional sulfite and developing agent that are consumed in the process, provide additional alkali to make up for loss, but reduce the amount of or omit bromide to compensate for that added to the developer as the result of the development reaction. In general, long-running processes can be maintained by suitable control of the chemistry through sensitometric monitoring and analysis of the constituents of the developer in use. In many instances, the carry-over of solution from the

tank is sufficient to accommodate the replenisher solution introduced into the tank, but in some instances control is achieved by having the formulas adjusted so that some additional developer has to be withdrawn to permit the introduction of a greater amount of replenisher. This makes it possible to adjust the withdrawal rate as another means of controlling the developer's chemical composition. In some cases, it may be necessary to remove more than is carried over by the film to compensate for excessive buildup of halides beyond that required in the original formula.

Large-scale operations with continuous processing require constant chemical and sensitometric monitoring, as well as careful adjustments in the replenisher formula and rate in order to maintain the result within narrow limits. Since the rate of replenishment depends upon the type of film being processed, and the type of images on the film (high-density vs. low-density, etc.), these factors must be considered in maintaining uniformity—particularly in the case of color processes.

Process control procedures used to maintain consistent quality involve sensitometric tests and chemical analysis of the processing solutions.

Paper Processing

The developers used for papers generally follow the same principles as those for films, with additional problems because of the physical differences (which govern carry-over, among other things). Alkalinity and other aspects of the developer may affect the sizing, curl, and/or brittleness of the paper. The content of the developer—restrainers and reaction products—can have a significant effect on the tone of the image produced, and this can become more apparent if the prints are subsequently chemically toned.

Selecting a film developer commonly involves a trade-off, such as fine-grain versus short developing time.

Analysis of Developers

The best control of processing operations involves the use of both sensitometric tests and chemical analysis of the processing solutions, techniques of process control (see Chapter 3). However, the analysis of most photographic chemistries involves rather complicated procedures and requires a well-equipped laboratory operated by a trained chemist. In addition, some methods are subject to error due to the presence of other chemicals in the solution. It is best to continually make reference to a properly mixed operating solution that has not been used to make sure the calibrations of the analyses are accurate. Simple procedures include the measurement and control of pH, measurement of specific gravity, and notation or measurement of the color of the solutions. These can be plotted and serve as an indication of change that may call for further study or more advanced analysis. And, of course, because all chemical processes are a function of time, temperature, and, in the case of photography, agitation, carefully monitoring these aspects is probably the most important control that can be exercised.

The importance of good darkroom habits cannot be overstressed. Most failures of photographic processes can be attributed to accidents involving contamination of the processing solutions, even in trace amounts.

Specific Black-and-White Processes

Processing of black-and-white films, papers, and plates normally involves development, followed by a rinse in an acid stop bath, fixing in an acid

Table 15-1 Some developer formulas compared

	DK-50	DK-50R	D-76	D-76R	D-76d	A-17	D-25	DK-20	DK-20R	D-72	D-85
Water (liters)	0.750	0.750	0.750	0.750	0.750	0.750	0.750	0.750	0.750	0.750	0.750
Metol	2.5 g	5.0 g	2.0 g	3.0 g	2.0 g	1.5 g	7.5 g	5.0 g	7.5 g	3.1 g	
Sodium sulfite	30.0 g	30.0 g	100.0 g	100.0 g	100.0	80.0 g	100.0 g	100.0 g	100.0 g	45.0 g	30.0 g
Hydroquinone	2.5 g	10.0 g	5.0 g	7.5 g	5.0 g	3.0 g				12.0 g	22.5 g
Sodium metaborate[a]	10.0 g	40.0 g						2.0 g	20.0 g		
Borax			2.0 g	20.0 g	8.0 g	3.0 g					
Sodium carbonate[b]										80.0 g	
Boric acid					8.0 g						7.5 g
Sodium bisulfite							15.0 g				2.2 g
Paraformaldehyde											7.5 g
Sodium thiocyanate								1.0 g	5.0 g		
Potassium bromide	0.5 g					0.5 g		0.5 g	1.0 g	2.0 g	1.6 g
Water to make	1 liter	1 liter	1 liter	1 liter	1 liter	1 liter	1 liter	1 liter	1 liter	1 liter	1 liter

[a] Kodak
[b] Monohydrated

thiosulfate solution, washing to remove the soluble silver complexes and processing chemicals, and then drying. The wide choice of developer formulas depends on the photographic objectives, economic considerations (time, overhead), quality advantages (real or imagined), safety, ecological considerations, etc.

Paper-processing formulas are designed to produce pleasing image tone and densities, both before and after chemical toning; to have good tray or machine tank life; and freedom from unwanted stain or fog in the whites of the print. Color formulas have to be capable of forming appropriate dyes of good density. In some applications, film speed is the primary criterion, and the formula may be chosen to maximize this characteristic, even at the sacrifice of some aspects of image quality. In most cases there has to be a *trade-off* between desired attributes and those that are required to meet some condition. Table 15-1 compares some typical developer formulas.

Practical Applications

Understanding the process by which both film and paper are developed is only part of picture. Understanding the effect it has on your photographs is the rest. Although the chapter on Tone Reproduction has gone into this in detail, it is worthy of a brief discussion here.

The assumption made here is that the starting negative is properly exposed. Let's begin with a normal reactive developer at the proper temperature with proper agitation.

The effect of underdeveloping film will cause an overall drop in contrast of the resulting negative and the final print. This is caused by an insufficient amount of time for the exposed silver halide crystal to be developed into metallic silver. The highlight areas of

the image, which should have a high density in the negative, are not given sufficient time to build up the density required to produce bright, clean highlights in the final print. The shadow areas that have detail in them are lost in the final print also, again due to insufficient time for the developer to produce separation in densities in these areas.

Overdeveloping film will often increase the contrast of the negative, but still not produce a satisfactory result. Overdeveloping can allow the developer to start to react with non-exposed silver halide crystals, building up density where it should not be.

REVIEW QUESTIONS

1. The development process amplifies the latent image silver by as much as . . .

   A. one hundred times
   B. one thousand times
   C. one million times
   D. one billion times
   E. one trillion times

2. The basic steps in reversal processing, in the correct order, are . . .

   A. develop, fix, bleach, re-expose, redevelop, fix
   B. develop, bleach, re-expose, redevelop, fix
   C. re-expose, develop, bleach, redevelop, fix
   D. develop, re-expose, bleach, redevelop, fix

3. In chemical development, the silver that forms the final image is provided by . . .

   A. a pre-development toning bath
   B. the developer
   C. the latent image
   D. the silver halide grains
   E. the fixer

4. Developing agents are classified as being . . .

   A. oxidizers
   B. reducers
   C. ambivalent

5. “Superadditivity” refers to the effect produced by using . . .

   A. Metol and Phenidone in the same developer
   B. Metol and hydroquinone in the same developer
   C. double the normal amount of Metol in a developer
   D. Metol and sodium sulfite in the same developer

6. The chemical most commonly used as a preservative in developers is . . .

   A. potassium bromide
   B. sodium sulfate
   C. sodium sulfite
   D. sodium sulfide
   E. sodium thiosulfate

7. Benzotriazole, which is sometimes used in developers, is classified as . . .

   A. a developing agent
   B. a preservative
   C. an alkali
   D. an anti-foggant
   E. an accelerator

8. In comparison with the original developer, developer replenishers typically contain . . .

   A. less preservative
   B. less restrainer
   C. less alkali

chapter

16 Archiving Photographic Images

"Spirit Island" by Lydia Richards, Fine Art Photography student Rochester Institute of Technology.

Introduction

Archiving images has different meanings to different photographers. To some it means the processes that one must go through to preserve negatives and prints for eternity. To others it means choosing a digital backup system that will be compatible with the ever changing technologies. We will explore both.

Digital Images

Archiving digital images is a necessary task for every photographer, from the amateur using a simple point and shoot camera to the professional using a high-end SLR camera. The digital environment and the many software packages available for image manipulation has brought photography into the hands of everyone, as was the goal George Eastman. However, if your image collection is not properly archived, one disk failure could mean the loss of everything. Likewise, editing an image and writing it back to the same file could also mean the loss of the original image (your digital negative) forever.

There is no set standard to digital archiving. The term *archiving* in this case is misleading. Technology changes so quickly that maintaining a digital archive is a constant process. Often a digital image archive is a stored on the highest quality affordable technology currently available. Recall in the digital realm we started with floppy disks, then went to zip drives, and are now at DVDs. It would be difficult to find a functional floppy disk drive today. Therefore, a digital archive must be constantly maintained and updated as often as technology dictates. To be successful in this process a workflow should be established and followed. An example is provided in Figure 16-1.

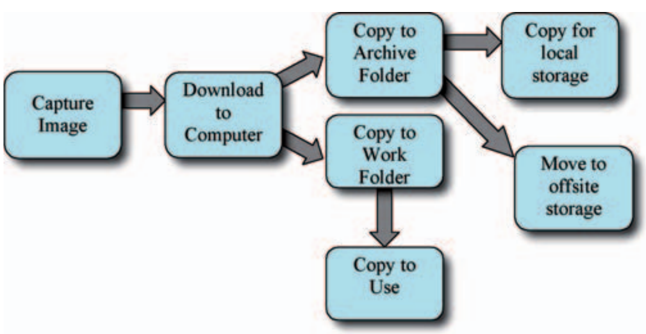


Figure 16-1 Proposed digital archive workflow.

The workflow in Figure 16-1 starts with the capturing of an image. This may seem simple, but there are considerations here. If the camera has multiple file formats, which one should be selected? From a photographer's point of view, the native RAW format might be best for original image capture but perhaps not for long-term storage. We will discuss this further later in this section and additional information can be found in Chapter 3.

Moving the images from the camera to the computer in the next step. The approach provided makes two copies of the images, one in a folder that is set for archive only and one that is for general use. The decision on what file format to use for the image archive must be made.

Archiving the images in the manufacturer's native RAW format is an option, but it carries some risk with it. Currently all major camera manufacturers have their own proprietary RAW format. As they find more efficient methods for creating the RAW image files, the formats change. In the future an image archived in a RAW format may become inaccessible as software support for older formats is discontinued. There has been proposed an OpenRAW format,[1] which is

[1] For more information see http://www.openraw.org

a standard format that would solve this problem. None of the major camera manufacturers have chosen to participate in this format at the time of this publication.

An additional format option that is gaining popularity is the DNG (digital negative) introduced by Adobe in 2004. This is a royalty-free RAW format that has been adopted by some of the bigger camera manufacturers.

Choosing a file format that compresses the data will save space, but the original image data can never be recovered, which could result in a loss of image quality and the ability to effectively enhance the image. There are two common file formats, tiff and JPEG 2000 without compression that will preserve the original digital data and have been standardized industry-wide. The use of a common standardized format would reduce the likelihood of having to reformat images in the future.

The last step in archiving digital images is to make copies of the data. There are many options available today. Two copies should be created, one to keep local for easy access and one to store at another location to prevent the loss of all data in the event of a local catastrophe such as a fire. Local storage options such as placing the data on a hard drive or RAID (redundant array of independent disks) would allow the easy retrieval of original data if needed. The need for easy access is important as everyone will occasionally write over original data or delete a file by mistake. The use of CDs or DVDs is a common choice for offsite storage, as they are easy to transport. The lifetime on these types of media range from 20 to 50 years if stored as the manufacturer suggests.

The key to successfully creating and maintaining a digital archive is to develop a workflow and follow it. The ability to have the original data exist in several locations ensures that a complete loss of data is unlikely.

Storing multiple copies of digital data at separate locations will guard against complete loss of data due to a local catastrophe such as fire.

Silver Image Archiving

Before we discuss the process of archiving silver-based images, we must briefly discuss the development process and the chemical processes involved.

Stop Baths

After removing film or paper from the developer it is placed in a stop bath. A stop bath consists of a mild acid, with a pH of 3 to 5, that neutralizes the alkali of the developer and stops development. An acid fixer also provides stopping action but after a quantity of developer has been carried over to the fixer, the acid is neutralized, the aluminum of the hardener will precipitate out as a sludge, and the stopping action is no longer precise. A water rinse before either the stop bath or the acid fixer will remove some of the developer, and prolong the life of either, but then the stopping action is drawn out and imprecise. A stop bath may also contain some hardening agent, and thus becomes an acid hardening stop bath. The most commonly used stop baths consist of 1.4–4.5% solutions of acetic acid, although a solution of sodium or potassium bisulfite is sometimes used. Some contain other additions.

An indicator dye used in an acid stop bath will change color when the acid has been neutralized by developer carry-over.

The two-bath fixing procedure enhances the archival quality of photographic prints.

Dichroic Fog

A fixer whose acid strength is at or near exhaustion will no longer effectively stop the developing action. As a result, some development will proceed at the same time as some silver halide is being dissolved by fixation, and dichroic stain, which is mostly

silver in the colloidal or near-colloidal state, will be produced. *Dichroic* means that it has two different colors, one by reflected light and the other by transmitted light.

Fixing Baths

A *fixing bath* converts the relatively insoluble silver halide in the film or paper into a soluble complex of silver that can be washed out of the emulsion layer, baryta layer, and paper fibers, to make the negative or print stable. Otherwise, the undeveloped silver halide would not only reduce the contrast of a negative, but it would darken in time and destroy the image. Sodium, ammonium, or (sometimes) potassium thiosulfate are the compounds most commonly used in fixing baths, although sodium thiocyanate and sodium cyanide have been used. (The latter is a hazardous compound and therefore is not recommended for use in photography.)

Excessive fixing can bleach silver images.

Removal of the by-products of fixation from fiber-base prints is made more difficult by overworking the fixing bath or over-fixing the prints.

A 2% solution of sodium sulfite is an effective washing aid for fiber-base prints.

When a fixing bath is used to fix films or prints, silver ions accumulate in the solution, which exert a force in the opposite direction and thus slow down the rate of fixation. If this accumulation is carried far enough, a point is reached where the soluble complex is not completely formed in the time allotted to fixation. If the fixing time is increased, the insoluble complex is adsorbed to the gelatin of the emulsion, the baryta coating if there is one, and the fibers of the paper base. The insoluble complexes are thus not removed by washing, and the silver can later be reduced by environmental factors to produce unwanted color and/or density. The presence of this reduced silver can affect the metallic silver image and cause it to become sulfided, thus changing color and losing density. Therefore, to ensure stable photographic images, it is important that the fixing solution not be worked beyond its capacity. The use of a two-solution fixing technique, whereby the prints are first bathed for a time in a fixing solution, then transferred to a second, fresher fixing solution, assures that the silver halide is converted to a soluble complex. After some time, the first fixer is discarded (or consigned to silver recovery), the second fixer becomes the first fixer, and a fresh fixing bath is added.

Washing

After fixing, photographic materials have to be washed to remove any of the fixing chemicals remaining as well as the silver compounds that have been formed during the fixing reaction. The problem is not a simple one. The chemical reactions leading to a soluble silver complex pass through steps in which insoluble complexes are formed, and these have to be fully converted to the soluble compounds. In addition, these complexes have a pronounced tendency to adhere to or be adsorbed by the fibers and baryta coatings of ordinary papers (see Figure 16-2). Films and polyethylene- or resin-coated (RC) papers do not generally present this problem except to the small extent that it may occur in gelatin coatings. For these reasons, the fixing step should be for the minimum time that will ensure that the reaction goes to completion to prevent any appreciable adsorption of the chemicals.

As the fixing process continues, and more silver complexes accumulate in the fixing bath, the tendency increases for the reaction to be forced in the reverse direction. In general, the fixing bath will perform well when the total amount of silver (in the form of ions from residual silver thiosulfates) in the bath is below 2.0 grams/liter. Films and resin-coated papers are readily washed, as they do not have fibers or baryta

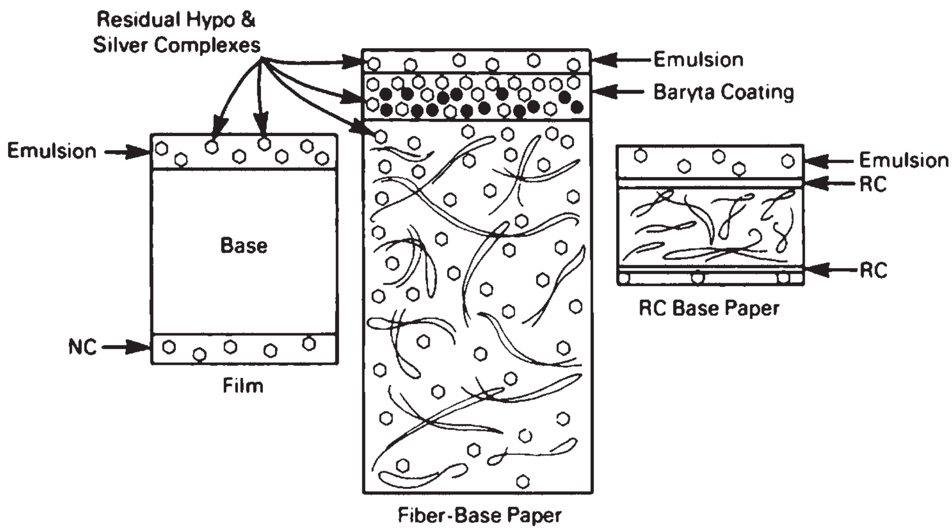


Figure 16-2 Baryta-coated fiber-base papers retain some residual hypo and silver complexes. Films do not contain a baryta coating or paper fibers, and RC-base papers have protective resin coatings on both sides of the paper base.

coatings exposed to the solutions for adsorption to take place. Fiber-base papers may not be completely washed even after 60 minutes of washing under ideal conditions, whereas films are usually washed in 20 to 30 minutes under similar conditions and resin-coated papers in 4 minutes, provided the wash-water flow rate is sufficient to give the required number of changes. The specific gravity of a typical fixer is in the vicinity of 1.18. However, with a reasonable flow of water the fixer does not have a chance to settle to the bottom of the wash tank.

Preparation for Drying

After films or papers are washed for the time necessary to remove residual thiosulfate or thiosulfate-silver complexes, they should be carefully dried. This aspect of the photographic process is often neglected to the extent that it subtracts substantially from the quality and acceptability of the final product. Fiber-base papers absorb considerable water during washing, and this has to be removed in the drying process. RC (resin-coated) papers, on the other hand, absorb very little water, and this is restricted to the thin emulsion and NC (non-curl) coatings. These materials dry very rapidly—in a matter of a few minutes.

Films washed in clean water can be hung up to dry without wiping. However, if drops of water are allowed to remain on the film, drying marks or deformities in the image will form because of differential shrinking of the gelatin around the edges of drops on the emulsion side that will be difficult, if not impossible, to remove. Excess water droplets and sediment in small amounts can be removed with a clean moist sponge or chamois by carefully wiping the surfaces, but if care is not used, this procedure may put more contamination on the negative than it removes.

In large laboratories where the film is processed in a serpentine fashion in continuous lengths, excess moisture is blown off by an air jet or squeegee. Water spots on sheet films and individual rolls can be avoided by using a wetting-agent bath before drying, which spreads the surface layer of water so that no droplets are formed. Kodak Photo-Flo™ is one such product. This bath, if made with filtered or otherwise

Drying marks from drops of water on film while drying are difficult, if not impossible, to remove.

clean water, can also serve as a rinse to remove some sediment. Gently rubbing the film surfaces as they are removed from the wash water can dislodge particles that may tend to cling to them.

Drying Films

It is best to dry films at room temperature—but this procedure may require an inconveniently long time in some situations so that heat is often applied, along with air circulation, to hasten the drying process. At the start of drying, relatively warm air can be used, as evaporation of the moisture in the film has a cooling effect. As drying progresses, high temperatures should be avoided. If the temperature is too high, drying will become excessive, and the film may become brittle and curl excessively. Other damage to the film may also occur. The air should be filtered to prevent the accumulation of dust on the film surfaces. A large volume of relatively pure air can carry a substantial number of particles that could be attracted to the wet film. This attraction can be accentuated by the electrostatic charge built up in the film by the air flowing over its surfaces.

Some photographic prints appear darker when dry than when wet.

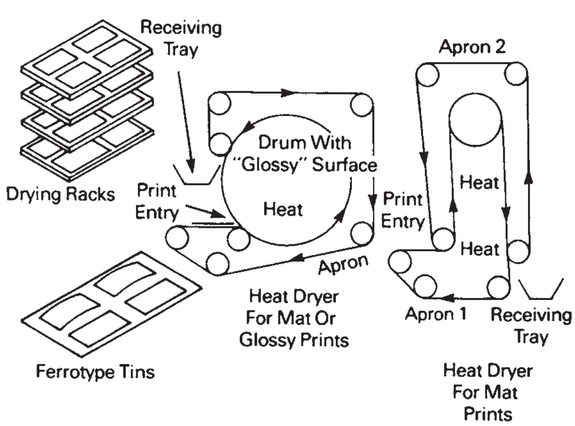


Figure 16-3 Paper drying.

Drying Prints

Similar precautions apply to the removal of excess water from the surfaces of prints that are to be dried. Print-drying machines usually have squeegee rollers at their entrances that remove excess surface water. RC or resin-coated papers carry relatively little water and can be dried quite rapidly, within a few minutes without heat, after the excess water has been removed. Fiber-base papers, on the other hand, can carry a relatively great load of water, which has to be removed. Air drying the prints at room temperature on clean cheesecloth or racks is probably the least destructive to the image and the physical quality of the prints. However, if the relative humidity is high, this kind of drying process is apt to be excessively long. For this reason, most photographic installations make use of heat dryers of one form or another (see Figure 16-3).

Preservation of Photographs

The chief factor in the preservation of silver photographic images is the total removal of silver complexes and hypo from the print by washing, before drying. After that it is important that the print not be exposed to any contaminant that would react with the silver image. The choice of adhesives for mounting, if the print is mounted at all, is important. Some kinds of glues and pastes, especially those that might contain sulfur, should never be used. Hygroscopic materials (substances that absorb water from the air) should not be used. Dry-mounting tissues especially designed and marketed for mounting photographs are generally acceptable. But even this type of mounting may eventually detract from the value of the photograph if it becomes a collector's

item. The best recommendation seems to be that of using archival materials (mounting and matting boards, and cloth tape) to suspend the print under a mat, then in a frame under glass for display. If the mat has to be replaced after some handling, it is a simple matter to remove the print and re-mat it.

Sometimes the photographic print is only an intermediate image for use in preparation of plates for printing in catalogs, magazines, or newspapers, and once these plates have been prepared, the photograph is no longer needed. In the motion-picture industry, the release prints need only last as long as the physical capability of the film to sustain screenings—about 500 to 1000 projections—after which it is destroyed. However, if the images are expected to have some value in later years, other precautions have to be taken. The photographer will need to make sure the print is made to have archival permanence, and the motion-picture companies will have to have their prints made on film with dyes that will hold up under long-term storage, or have separations made on black- and-white film that can be stored and then brought out for regeneration of the color films at a later date.

Storage containers, mat boards, and mounting boards are potential sources of agents that are deleterious to photographs. For this reason, if photographs are to be stored for any time, they should be packed in properly designed containers made of inert materials. Old film and paper boxes should not be used; neither should wooden and cardboard cases. Metal cases coated with paints that do not give off any fumes, or cases made of inert or acid-free-board, should be used. Mount and mat boards should be inert and acid-free; that is, buffered to a slightly higher than neutral pH for black-and-white photographs. However, there may be some question in using this type of material for color photographs, since most of these dyes may survive best under slightly acid or nearly neutral conditions.

It is important that the storage area's atmosphere be maintained with moderate or lower temperatures, and low relative humidity (below 50 percent). The cyclic effect of day and night conditions—wet then dry, winter then summer—contributes more to rapid deterioration than when these conditions are maintained at a desirable low humidity and temperature with a small cyclic variations.

Even properly processed prints are susceptible to being damaged if exposed to certain contaminants.

Some toners increase the archival qualities of photographic prints; others decrease it.

REVIEW QUESTIONS

1. Failure to use a stop bath for quantity processing of prints may result in . . .
   A. fogged prints
   B. contrasty prints
   C. discolored prints
   D. sludge in the developer
   E. sludge in the fixer
2. The pH values of stop baths are usually in the range of . . .
   A. 2 to 4
   B. 3 to 5
   C. 4 to 6
   D. 5 to 6
3. In the two-solution fixing procedure, the fresher fixing bath is in the . . .
   A. first position
   B. second position
4. The recommended method of extending the life of a fixing bath is to . . .
   A. heat the bath to 100° F
   B. add replenisher
   C. remove the silver
5. Hypo eliminators work on the principle of . . .
   A. causing thiosulfate ions to precipitate
   B. neutralizing the static electrical charge on the thiosulfate ions
   C. converting thiosulfates to sulfates
   D. producing a molecular oscillation

6. With respect to image stability, toned images . . .

   A. are more stable than silver images
   B. are less stable than silver images
   C. vary considerable in stability

7. If a negative of a normal-contrast subject that was correctly exposed but overdeveloped is to be reduced, it should be reduced in a . . .

   A. proportional
   B. sub-proportional reducer
   C. super-proportional reducer

chapter

17 Variability and Quality Control in Photography

"Bee on Flower" by K.T. Evans, Advertising Photography student, Rochester Institute of Technology.

Introduction to the Concept of Variability

Photographers are by necessity experimenters. Although they are not thought of as scientists operating in a research atmosphere, they certainly are experimenters. Every time an exposure is made and the negative is processed or a digital image created, an experiment has taken place. There is no way the photographer can precisely predict the outcome of such an experiment in advance of doing the work. The objectives of the experiment derive from the purpose of the assignment, and the procedures come from the photographer's technical abilities. The success of the experiment will be determined by evaluating the results. Finally, conclusions are reached after interpreting the results, which will shape the performance for the next assignment/experiment. It is the last step, the interpretation of test results and the conclusions reached, that we are concerned with in this section.

A great deal of what is written about the practice of photography consists of opinions. When someone states that "black-and-white photographs are more artistic than color photographs" or that "digital cameras are better than film cameras," it represents an expression of personal judgment. Such statements are referred to

No two things or events are ever exactly alike.

as *subjective* because they are based on personal opinions. Opinions are statements of personal feelings and can be neither right nor wrong and therefore are always valid. The problem with subjective opinions is they lead to conclusions that are not easily tested and analyzed. Therefore, when one relies solely on personal opinion, the possibilities for obtaining new insights into the photographic process become very limited.

Subjective opinions have the potential to be ambiguous; therefore, it is often preferable to use numerical expressions that have been derived from measurements. Such numbers can be considered objective, as they are generated outside of personal attitudes and opinions. For example, the blackness of a photographic image can be measured with a densitometer and the result stated as a density value. A density value used to describe the blackness of a photograph can be obtained by independent workers and therefore verified. Although there may be many subjective opinions about the blackness of the image, there can be only one objective statement based on the measurements. Consequently, a goal of anyone who is experimenting is to test opinions with facts that usually are derived from measurements.

Variation in a repetitive process can be attributed to change, an assignable cause, or both.

When an experiment is completed and a result obtained, there is a great temptation to form a conclusion. For example, a new digital camera is tried and the noise level in the image is considered unacceptable; most photographers would not want to purchase it. On the other hand, if the image were taken at an ISO setting of 1000, many would assume that the same noise would not be present at an ISO setting of 100. Such conclusions should be resisted because of a fundamental fact of nature: *No two things or events are ever exactly alike*. No two persons, not even identical twins, are exactly alike and no two snowflakes are ever identical. Photographically speaking, two rolls of the same brand of film are not exactly alike, nor are the digital sensors of two cameras of the same make and model. If two samples are inspected closely enough, differences will always be found. Stated more directly, variability always exists.

In addition to these differences, time creates variations in the properties of an object. The photographic speed of a roll of film is not now what it was yesterday, nor will it be the same in a few months. Using this point of view, an *object*, say a roll of film, is really a set of events that are unique and will never be duplicated. As the Greek philosopher Heraclitus long ago said, “You cannot step in the same river twice.”

Knowing that variability is a fact of life it is an essential task for a photographer/experimenter to determine the amount of variability affecting the materials and processes being used. This will require that at least two separate measurements be made before reaching a conclusion about the characteristics of an object or process. A photographer who ignores variability will form erroneous conclusions about photographic materials and processes, and will likely be plagued by inconsistent results.

Sources of Variation

In an imaginary gambling situation in which a perfect roulette wheel is operated with perfect fairness, the outcome of any particular spin of the wheel is completely unpredictable. It can be said that, under these ideal circumstances, the behavior of the ball is determined by *random* or *chance causes*. These terms mean that there are countless factors influencing

the behavior of the wheel, each of which is so small that it could not be identified as a significant factor. Consequently, these numerous small factors are grouped together and identified as chance effects and their result is termed *chance-caused variability*. In addition to being present in games of chance, chance-caused variation occurs in all forms of natural and human undertakings.

Consider, on the other hand, a rigged roulette wheel, arranged so that the operator has complete control over the path of the ball. Under these circumstances, there would be a reason (the decision of the operator) for the fall of the ball into any particular slot. With this condition it is said that there is an *assignable cause* for the behavior of the ball.

The distinction between these types of effects—*chance* and *assignable* cause—is important, because it will influence the actions taken. For example, your desire to play the roulette wheel would likely disappear if you believed the operator was influencing the results. A similar dilemma arises when, for example, an electronic flash fails to fire. A second photograph is taken and again the flash fails. If this procedure is continued, it would be based upon the assumption that it was only a chance-caused problem. On the other hand, if the equipment were examined for defects, the photographer would be taking action with the belief that there was an assignable cause for the failure of the flash, such as depleted batteries or a broken bulb.

In other words, when it is believed that chance alone is determining the outcome of an event, the resulting variation is accepted as being natural to the system and likely no action will be taken. However, if it is believed that variability is due to an assignable cause, definite steps are taken to identify the problem so that it can be remedied and the system returned to a natural (chance-governed) condition. Therefore, it is very important to be able to distinguish chance-caused from assignable-caused results.

Patterns of Variation

The expected pattern of variation with repeated spinning of an honest roulette wheel is unlikely to occur in practice.

Although there is no possibility of predicting the outcome of a single turn of a fair roulette wheel, there is an underlying pattern of variation for its long-term performance. If the ball has the same likelihood of dropping into each of the slots, then over a large series of plays each of the numbers should occur as frequently as any other. Thus, the expected pattern of variability for the long-term performance of the roulette wheel could be described by a graph as shown in Figure 17-1. This is called a *frequency distribution* graph because it displays the expected frequency of occurrence for each of the possible outcomes. In this case, it is termed a *rectangular distribution*, which arises any time there is an equal probability of occurrence for every outcome. Every one of the 38 slots has an equal chance of receiving the ball.

Suppose now that the roulette wheel is spun many times so that

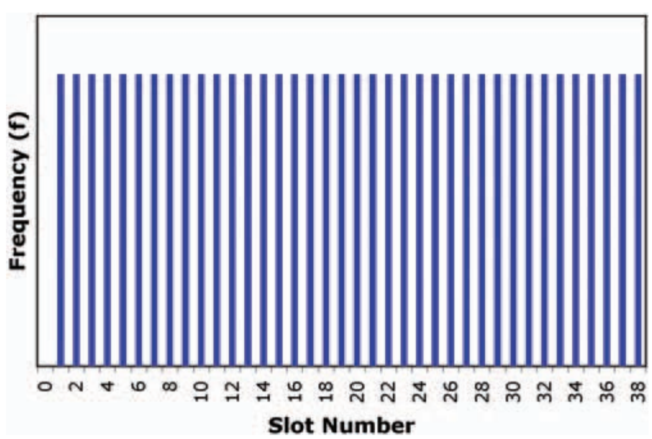


Figure 17-1 Rectangular pattern of variability from the expected long-term performance of a perfect roulette wheel. Each number has an equal chance of occurring.

Assignable-cause variability can be corrected; random-cause variability cannot.

the actual pattern of variation can be compared to the expected distribution. If the wheel is actually operated 380 times, it is highly unlikely that each number will occur exactly ten times. Instead, a pattern similar to that shown in Figure 17-2 will probably arise, indicating that the actual distribution only approximates that of the expected (or theoretical) results. It would likely be concluded from these results that the wheel is honest. However, if the actual distribution of 380 trials appeared as shown in Figure 17-3, there would be good cause to suspect something abnormal was happening. The distribution in Figure 17-3 show a tendency for the numbers 1 through 15 to occur more frequently than 16 through 38.

Thus, a basic method for judging the nature of variation in a system is to collect enough data to construct a frequency distribution (also referred to as a frequency histogram) and compare its shape to what is expected for the process. If the shapes are similar, the process is behaving properly. A significant difference indicates an abnormal condition that should be identified and corrected.

In the game of dice, if a single die is thrown repeatedly in a random manner, a rectangular distribution is also to be expected. Why? Each of the six numbers on the die is equally likely to occur on every roll. If two dice are used, a different pattern is expected since the probability of rolling a seven is greater than for any other number. In other words, there are more combinations that total seven than any other number (1 + 6, 2 + 5, 3 + 4, 4 + 3, 5 + 2, 6 + 1). The expected pattern is referred to as *triangular distribution* and is shown in Figure 17-4.

If this concept is extended to the totals of three dice, five dice, etc., the expected distributions begin to look like the symmetrical bell-shaped curve shown in Figure 17-5. This frequency pattern is called the *normal distribution*. It is of exceptional importance because

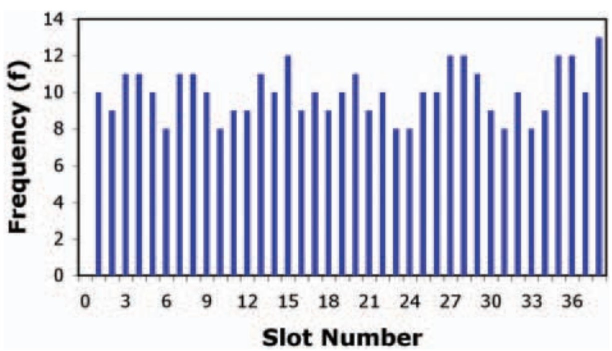


Figure 17-2 Pattern of variability from the actual performance of a roulette wheel indicating that only chance differences are occurring. Although theoretically each number has an equal chance of occurrence, some numbers occur more frequently over the short run.

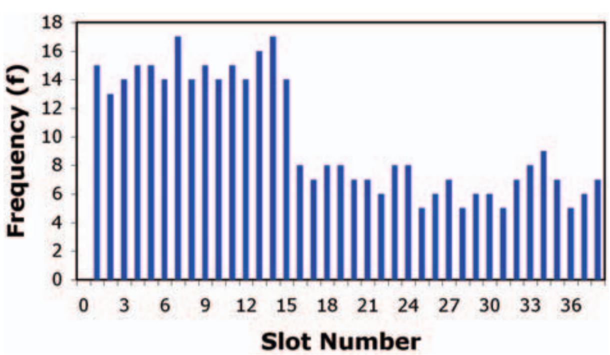


Figure 17-3 Pattern of variability from the actual performance of a roulette wheel indicating assignable-cause influence. The lower numbers are occurring more frequently that the higher numbers.

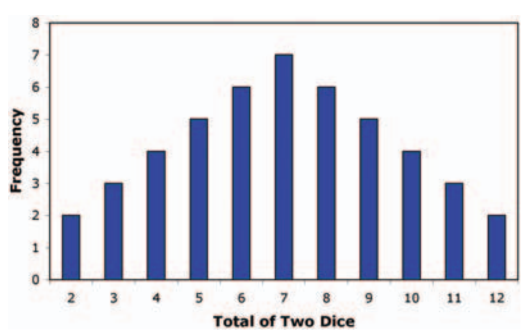


Figure 17-4 Triangular pattern of variability from the expected long-term performance of two randomly thrown dice.

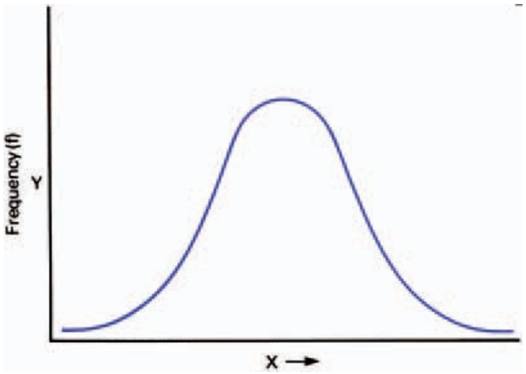


Figure 17-5 Expected pattern of variation when there is a multiplicity of outcomes with chance governing the process. This bell-shaped curve is called the normal distribution.

whenever there are many outcomes with many factors affecting each occurrence, which is the case with almost all real-life events, this is the pattern suggested by chance. Consequently, when evaluating the results of tests and experiments using photographic materials, the normal distribution of data is the expected condition. If the results are something other than this bell-shaped pattern, it is an indication of assignable-cause problems and appropriate action should be taken.

Notice that to obtain a useful picture of the pattern of variation, more than a few samples must be collected. Statistical theory suggests that at least 30 samples should be used to construct the distribution before making any inferences, because the pattern that develops as additional samples are taken tends to stabilize at 30. For example, a slow film was tested and five samples gave speeds of 10, 12, 10, 14, and 14, producing the histogram shown in Figure 17-6. Although the resulting pattern is not a bell-shaped curve, there are too few samples to draw a valid conclusion. An additional 25 samples added to the first five could give the distribution illustrated in Figure 17-7. Here the pattern approximates the normal distribution, indicating that the differences in film speeds are only the result of chance-caused effects.

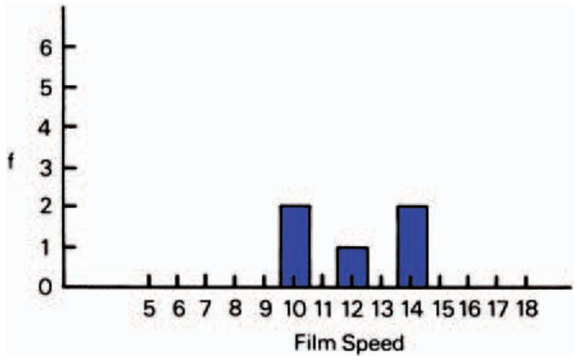


Figure 17-6 Frequency histogram of film speeds (5 samples).

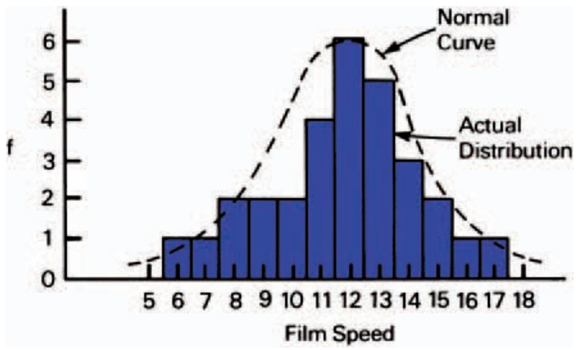


Figure 17-7 Frequency histogram of film speeds (30 samples).

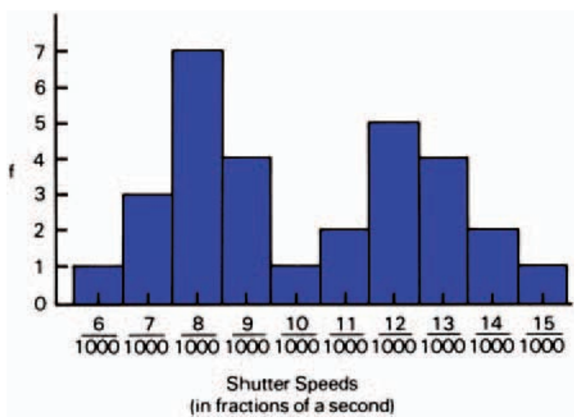


Figure 17-8 Frequency histogram of 40 different shutters tested at the same marked shutter speed of 1/125 (8/1000) second.

Suppose the results of testing 40 different shutters at the same marked shutter speed gave a set of data distributed as shown in Figure 17-8. The pattern exhibited differs markedly

The normal-distribution curve represents the expected pattern of random-cause variability with a large amount of data.

from the normal distribution; thus it is inferred that something unusual is occurring. The two peaks in the histogram suggest the presence of two sources or populations of data, such as two different types of shutters.

Consider the histogram shown in Figure 17-9, which is the result of testing the same meter 35 times against a standard light source. Notice that the distribution is asymmetrical—the left-hand "tail" is longer than that on the right. Again, it should be concluded that there is an assignable cause in the system. Perhaps because of a mechanical problem the needle is unable to go above a given position, hence the lack of data on the high side. In both of these instances, because the bell-shaped distribution did not occur, a search for the assignable cause is necessary.

The Normal Distribution

The values of the mean, the median, and the mode will be the same for a set of data only when the data conform to a normal distribution.

After a histogram has been inspected and found to approximate the normal distribution, two numbers can be computed that will completely describe the important characteristics of the process.

The first of these is the arithmetical *average* or *mean*. The mean is obtained by adding all of the sample data values together and dividing by the number of samples taken. The resulting number or mean is the value around which the rest of the data tend to cluster. The mean is a measure of the central tendency of the distribution. See Eq. 17-1.

$$\bar{X} = \frac{\sum \text{Sample Values}}{\text{Total Number of Samples}} \tag{Eq. 17-1}$$

There are two other measures of central tendency that are sometimes used to describe a set of data. The *mode*, which is defined as the most frequently occurring value in a data set, is located at the peak of the histogram. The *median* is that value that divides the data set into two equal halves. Of all three measures of central tendency, the average is by far the most often used.

It is sometimes useful to represent variability with the simpler concept of the relationship between the smallest value and the largest value in a set of data. For data that are measured with interval scales, such as temperature, length, and weight, the difference between the largest and smallest values is identified as a *range* (see Eq. 17-2). For data that are measured with ratio scales, such as the contrast of a scene, the largest value divided by the smallest value is identified as a *ratio* (see Eq. 17-3). Thus the contrast of a certain scene might be expressed as having a luminance ratio of 128:1.

$$\text{Range} = \text{Largest Value} - \text{Smallest Value} \tag{Eq. 17-2}$$

$$\text{Ratio} = \frac{\text{Largest Value}}{\text{Smallest Value}} \tag{Eq. 17-3}$$

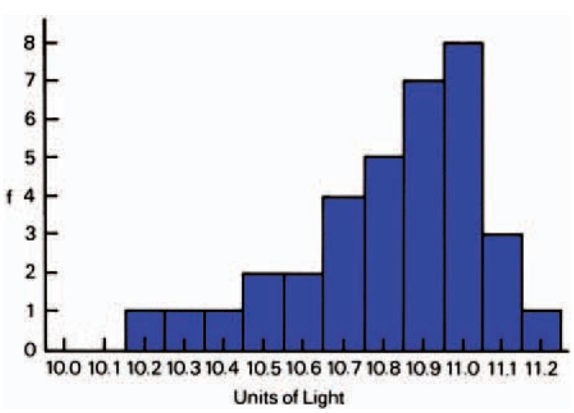


Figure 17-9 Frequency histogram from testing the same meter against a standard source 35 times.

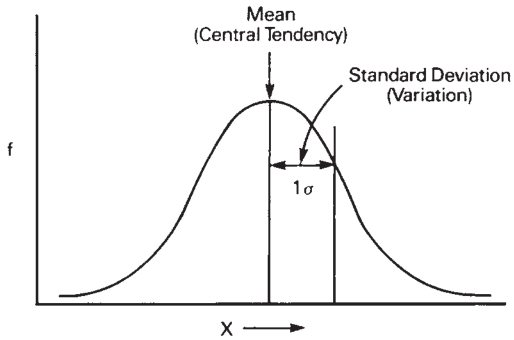


Figure 17-10 Theoretical normal distribution illustrating the relationship between the mean and the standard deviation.

The second number of interest is called the *standard deviation* and represents a measure of the variability of the system. To calculate the standard deviation, each individual sample value is compared to the average (or mean) and the average difference or deviation for all of the data is determined. This value is a measure of the width of the normal distribution. If the normal distribution is very narrow, the variation is small; if it is very wide, the variation is large. Thus, the standard deviation is a direct measure of the amount of variability in a normal distribution.

Figure 17-10 illustrates the relationship between the average and the standard deviation for a hypothetical normal distribution. Notice that if the distribution should shift left or right, this would be reflected in a change of the as that the central position of the system has changed. If the width of the distribution were to become narrower or wider, the standard deviation would change because the amount of variability in the system would be changing. Taken together, these two values can provide a useful set of numbers for describing the characteristics of any system tested.

Populations vs. Samples

Before continuing it is necessary to distinguish between *populations* and *samples*. If, for example, a new brand of inkjet paper were being marketed, one would want to test it prior to use. To obtain a crude estimate of the variability affecting this product, at least two samples should be tested. If it is desired to determine the pattern of variation, at least 30 should be tested. Even if 30 tests were performed (which would be quite a task), countless more boxes of paper would not be tested. Thus the term *population* refers to all possible members of a set of objects or events. Additional examples of populations are the ages of all U.S. citizens, the birth weights of all newborns, the ISO/ASA speeds of all sheets of Brand X film, the temperatures at all possible points in a tank of developer, and the accuracy of a shutter over its entire lifetime.

In each case, an extremely large number of measurements would have to be made to discover the population characteristics. Seldom, if ever, are all members of a population examined, primarily because in most cases it is usually impossible to do so. Further, by examining a properly selected group of samples from the population, almost as much insight can be obtained as if all members had been evaluated. Herein lies the value of understanding some basic statistical methods. By obtaining a relatively small number of representative samples, inferences can be made about the characteristics of the population. Such is the basis of much scientific investigation, as well as political polls.

Samples used to calculate the mean and the standard deviation must be selected on a random basis.

If the sample is to be truly representative, it must be selected from the population with great care. The principle to be followed is this: *Every*

*member of the population must have an equal chance of being selecte*d. When taking sample density readings from a roll of film after processing, for example, it is dangerous to obtain the data always from both ends and the middle. It is also dangerous never to obtain data from the ends and the middle. The samples must be selected so that in the long term data are obtained from all parts of the roll with no area being consistently skipped or sampled.

Although this principle appears simple enough, the method for carrying it out is not. The most common approach for ensuring that all members of the population have been given an equal opportunity is to use a random sampling method. *Random* means "without systematic pattern" or "without bias." Human beings do not behave in random ways but are strongly biased by time patterns and past experiences. Consequently, special techniques must be employed to avoid the non-random selection of samples. Techniques such as drawing numbered tags from a box, using playing cards, tossing coins, etc. can be used to minimize bias in obtaining samples. Tables of random numbers are also very useful in more complex situations.

It should be obvious that there is a distinction between the average of the population and the average of the sample data. The symbol μ (Greek letter mu) is used to refer to the population average, while the symbol $\bar{X}$ (bar) is used for the sample average. Likewise, there is a difference between the standard deviation of the population and that of the sample data. The symbol σ (Greek letter sigma) is employed for the standard deviation of the population, and the symbol s identifies the sample standard deviation. If the sample data are representative of that in the population, $\bar{X}$ and s will approximate μ and σ, respectively. Also, as the number of samples taken increases, the conclusions reached become more reliable. Table 17-1 displays the symbols and formulas employed.

Description of the Normal Distribution

The graph of the normal distribution model is a bell-shaped curve that

Table 17-1 Statistical symbols

Terms	Population (Parameter)	Sample (Statistic)
Number of observations	N	n
Mean (average)	μ (mu)	$\bar{X}$
Standard deviation	σ (sigma)	s
A single observation	X	X
Formulas		
Mean (average)	$\Sigma X/N$	$\Sigma X/n$
Standard deviation	$\sqrt{\dfrac{\sum(X-\mu)^2}{N}}$	Formula I $\sqrt{\dfrac{\sum(X-\bar{X})^2}{n-1}}$ Formula II $\sqrt{\dfrac{n\sum X^2-(\sum X)^2}{n(n-1)}}$
Where Σ = sum		

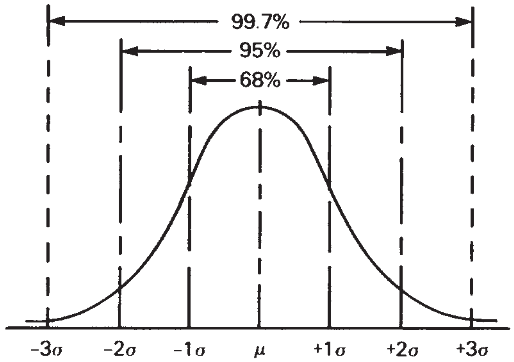


Figure 17-11 The normal distribution illustrating areas contained under the curve for ±1, 2, and 3 standard deviations.

extends indefinitely in both directions. Although it may not be apparent from looking at Figure 17-11, the curve comes closer and closer to the horizontal axis without ever reaching it, no matter how far it is extended in either direction away from the average.

An important feature of the normal distribution to note is that it is symmetrical around its *mean*. If Figure 17-11 were folded along the line labeled μ, the two halves of the curve would be identical. Therefore, the mean (μ) is the number that divides the population into two equal halves. Additionally, it can be seen that μ identifies the maximum point of the distribution. Consequently, the mean (μ) represents the best measure of the central tendency of the population.

When describing the spread of the normal distribution, the *standard deviation* (σ) is most useful. The standard deviation (σ) locates the point of inflection on the normal curve. This is the point where the line stops curving downward and begins to curve outward away from the mean. Since the curve is symmetrical, this position will be located at equal distances on both sides of the mean (μ). The total area contained under the curve would include all members of the population and is therefore equal to 100%. The standard deviation (σ) can be used to describe various portions of the population in conjunction with μ as follows:

Standard deviation is a single number that represents an average deviation from the mean for all of the individual numbers in a set of data.

1. The inflection points lie at ±1σ from the mean (μ). Between the inflection points are found approximately 68% of all members of the population. About 32% will be located beyond these points with 16% on the left and 16% on the right.
2. Approximately 95% of the population occurs between ±2σ of the mean. About 5% will be located beyond these points equally distributed on both sides.
3. Nearly 99.7% of the population will be between ±3σ of the mean. Only 0.3% will lie outside of these points.
4. As the distances on either side of the mean become greater, the percentage of the population contained therein likewise increases. However, it will never reach 100% because the curve never touches the horizontal axis.

Thus, a normal curve is completely specified by the two numbers, or parameters, μ and σ. In effect, μ locates the position of the curve along the X-axis, and σ specifies the spread of the curve. If the sample data obtained approximate the shape of the normal curve, and the sample size is large enough, the calculated values of $\overline{X}$ and *s* for the sample can be used the same way μ and σ are used for the population.

For example, suppose the repeated testing of a light meter against a standard source produced a set of data that approximated the normal distribution, and $\overline{X}$ is found to be 15.0 and *s* is equal to 1.0. With this information, it can be inferred that 68% of the readings will be between 14.0 and 16.0 caused by chance, 95% of the readings

It can be extremely useful to learn if meaningful relationships exist between objective measurements and subjective perceptions.

will be between 13.0 and 17.0 caused by chance, 99.7% of the readings will be between 12.0 and 18.0 caused by chance, while only 0.3% will be less than 12.0 and greater than 18.0 caused by chance.

If the meter were to be checked again and gave a reading of 13.5 (1.5 standard deviations from the mean of 15.0), the decision most probably would be that the meter was operating normally. In other words, the amount of variation in the reading is not greater than that suggested by chance. However, if the meter gave a reading of 18.5 (3.5 standard deviations from the mean), this would be viewed as an unusual occurrence and one that would call for a careful study of the equipment. This is because the difference is now greater than that suggested by chance, since only 0.3% of the readings will exceed $\pm 3s$ caused by chance.

This method of describing the characteristics of the materials and processes of photography minimizes guesswork and allows decisions to be made from facts.

Measurement Methods and Subjective Evaluations

All the concepts addressed so far have dealt with data resulting from objective measurements. Variables such as density, temperature, weight, and shutter speed are evaluated by using measuring instruments, and the results are expressed in relation to scales of numbers. These numbers are assigned on the basis of standardized units such as degrees Fahrenheit, centimeters, grams, etc. These types of measurements are referred to as *objective measurements* because they are derived from an external source (the measuring instrument) and are verifiable by other people using similar instruments.

Although objective measurements are commonly used to describe the physical properties of photographic materials and processes, they cannot be used to give information about the human perceptions of such properties. For example, when considering the tonal quality of a black-and-white print, reflection density measurements can be used to describe the print densities and contrast. However, these data give little insight into the way a person will perceive the tonal quality of the print, as that is a *subjective* experience. Obviously, the subjective quality of the photographic image is the final test of most photographic endeavors; thus it can be extremely useful to learn the meaningful relationships between objective measurements and subjective perceptions—especially the averages of the perceptions of samples of qualified individual observers.

When working with subjective concepts, it is the perception of the physical event that is being considered rather than the physical event itself. Nevertheless, numbers may be assigned to these perceptions to allow for their scaling and evaluation. Measurement, in the broadest sense, can be defined as the assignment of numbers to objects, events, or perceptions according to rules. The fact that numbers can be assigned under different rules leads to the use of different kinds of scales. All measurement scales can be classified as one of the following.

Nominal Scale

Nominal scales are essentially categories that are labeled with names, as when photographs are placed into categories such as portrait, landscape, indoor scene, outdoor scene, etc.

A nominal scale would also be obtained by assigning jersey numbers to baseball players since the number serves as a name. This is the most primitive of measurement scales, and therefore these data are not very descriptive.

Ordinal Scale

Ordinal scales have categories that are ordered along some variable and use numbers to represent the relative position of each category. When the results of a horse race are given as first, second, and third, an ordinal scale is being used. If photographs were rated according to their acceptability, the following ordinal scale could be used: (1) excellent, (2) acceptable, and (3) unacceptable. Notice there is no attempt to indicate how much better or worse the images are, just as there is no distance differentiation made between the winner of a horse race and the runner-up. All that is expressed is the order of finish. This approach is often referred to as rank-order or, more simply, "ranking" and is frequently used for scaling subjective responses. The graininess categories—extremely fine, very fine, fine, medium, moderately coarse, and coarse—constitute an ordinal scale.

Interval Scale

An *interval scale* is a refinement of the ordinal scale in which the numbers given to categories represent both the order of the categories and the magnitude of the differences between categories. Arithmetically equal differences on an interval scale represent equal differences in the property being measured. Such scales can be thought of as linear since they possess a simple, direct relationship to the object being measured. The Fahrenheit and Celsius temperature scales are excellent examples of interval scales; thus, a temperature of 80° F is midway between temperatures of 70 and 90° F. The interval scale is truly a quantitative scale.

Ratio Scale

Numbers on *ratio scales* increase by a constant multiple rather than by a constant difference as with interval scales. Thus, with the ratio scale of numbers 1–2–4–8–16, etc., the multiplying factor is 2. Incident-light exposure meters that measure directly in lux or foot-candles, and reflected-light exposure meters that measure directly in candelas per square meter or candelas per square foot, typically have ratio scales where each higher number represents a doubling of the light being measured. Some exposure meters use arbitrary numbers rather than actual light units on the measuring scale. If the arbitrary numbers are 1–2–3–4–5, etc., the scale is an interval scale.

The type of scale is determined entirely by the progression of the numbers, and not by what the numbers represent. A meter could even have two sets of numbers on the same calibrated scale, one a ratio scale of light units and the other an interval scale of arbitrary numbers. Other examples of ratio scales used in photography are shutter speeds (1–1/2–1/4–1/8–1/16, etc.) where the factor is 2, *f*-numbers (*f*/2–2.8–4–5.6–8, etc.) where the factor is the square root of 2 or approximately 1.4, and ISO film speeds (100–124–160–200–250, etc.) where the factor is the cube root of 2 or approximately 1.26.

Interval scales of numbers are somewhat easier to work with than ratio scales, especially when the ratio-scale sequence is extended and the numbers become very large (for

Rulers and thermometers use interval scales.

***F*-numbers and shutter-speed numbers on cameras represent ratio scales.**

Logarithms make it possible to avoid large numbers by converting ratio scales to interval scales.

2 plus 2 can equal 8 if the numbers represent exponents to the base 2.

When determining possible differences between two similar photographs, using a paired-comparison test can eliminate the effects of guessing.

The human visual system is most precise when making side-by-side comparisons.

example, 64–128–256–512–1,024, etc.) or very small (but never reaching zero). Converting the numbers in a ratio scale to logarithms changes the ratio scale to an interval scale. For example, the ratio scale 10–100–1000–10,000 converted to logarithms becomes the interval scale 1–2–3–4. This simplification is a major reason why logarithms are used so commonly in photography, where density (log opacity) is used in preference to opacity, and log exposure is used instead of exposure in constructing characteristic (D-log H) curves. DIN film speeds are logarithmic and form an interval scale compared to ratio-scale ISO speeds. The ISO speed system, which was adopted in 1987, uses dual scales (for example, ISO 100/21°) where the first number is based on an arithmetic scale and the second is based on a logarithmic scale. The APEX exposure system is also based on logarithms to produce simple interval scales (1–2–3–4–5, etc.) for shutter speed, lens aperture, film speed, light, and exposure values.

Exponential Scale

In addition to the four types of scales discussed above—nominal, ordinal, interval, and ratio—which cover all of the normal subjective measurement requirements related to visual perception and most of the objective measurements used in photography, there is another type of scale. Squaring each number to obtain the next extends the sequence of numbers 2–4–16–256, etc. This is called an *exponential scale* because each number is raised to the second power or has the exponent of 2.

Table 17-2 relates many types of photographic data to the appropriate measurement scale.

Paired Comparisons

One of the most basic techniques for evaluating subjective judgments is to present an observer with two objects (for example, two photographic images) and request the observer to make a choice based on a specific characteristic. The two alternatives may be presented simultaneously or successively, and no ties are permitted.

The simplest application of this method is the comparison of two samples, but it can be applied in experiments designed to make many comparisons between many samples. The results are expressed as the number of times each sample was preferred for all observers. If one of the two samples is selected a significantly greater percentage of the time, the assumption may be made that sample is superior relative to the characteristic being evaluated. How many times a sample must be selected to be considered superior is determined through statistical tables.

For example, consider the challenge of evaluating two black-and-white films for their graininess. Since graininess is a subjective concept, a test must be performed using visual judgment. The two films are exposed to the same test object and processed to give the same contrast. Enlargements are made from each negative to the same magnification on the same grade of paper. The two images are presented side by side and each observer is asked to choose the image with the finer grain. A minimum of 20 observers is usually needed to provide sufficient reliability for this type of experiment.

If the results of such an experiment were 10 to 10, the conclusion would be that there is no difference between the two samples. But if the

Table 17-2 Types of measurement scales

Type of Scale	Examples of Photographic Data
Nominal	• Emulsion identification numbers. • Classification of photographs into categories. • Serial numbers on cameras. • Names of colors, such as red, green, and blue. • Social security numbers of famous photographers.
Ordinal	• The scaling or grading of photographs along a rank order such as first, second, and third place or A, B, C, etc. • The rating of the graininess of photographs using the categories of microfine, extremely fine, very fine, fine, medium, moderately coarse, and coarse. • The ordering of photographs along a continuum such as lightest to darkest, largest to smallest, flat to contrasty.
Interval	• Temperature readings; degrees on a thermometer. • Hue, value, and chroma numbers in the Munsell Color Notation System. • Wavelength (nanometers) of electromagnetic radiation. • Contrast index values.
Ratio	• Shutter speeds. • *F*-numbers. • Exposures in a sensitometer. • ISO/ASA film speeds.
Exponential*	• Depth of field vs. object distance. • Depth of field vs. focal length. • Illuminance vs. distance from a source (inverse-square law). • Cosine law of light falloff in a camera.

*Although these represent exponential relationships, numbers are not normally presented in exponential scales due to the difficulty of interpolating.

results are 20 to 0, it can be concluded that one of the images actually had finer grain. A problem arises with a score such as 12 to 8 because such a score could be the result of chance differences only. The purpose of this test is to distinguish between differences due only to chance and those resulting from a true difference.

The conclusions from these tests must be based upon the probabilities of chance differences. Table 17-3 may serve as a guide for making such decisions. Column n refers to the number of observers. The columns titled *Confidence Level* identify the degree of confidence indicated when the conclusion is that a true difference exists. The numbers in the body of the table give the maximum allowable number of times that the less frequent score may occur. Therefore, in this example where 20 observers were used, the less frequently selected photograph may be chosen only five times if 95% confidence is desired in concluding that a difference exists. If a higher level of confidence is desired, say 99%, then the less frequently selected photograph can be chosen only three times. Notice that a score of 12 to 8 would lead to the conclusion that there was

Table 17-3 Maximum allowable number of wins for the less-frequently chosen object in a paired comparison test (or approximately a 2:1 ratio) would be needed. The increase in sample size provides greater sensitivity, which allows for better discrimination

Number of Observers	Confidence Level		
n	90%	95%	99%
8	1	0	0
9	1	1	0
10	1	1	0
12	2	2	1
14	3	2	1
16	4	3	2
18	5	4	3
20	5	5	3
25	7	7	5
30	10	9	7
40	14	13	11
50	18	17	15
75	29	28	25
100	41	39	36

no significant difference between the two images even at the lower 90% confidence level. The price that is paid to obtain greater confidence in the decision is that a greater difference must be shown between the two samples. If the number of observers were increased to 50, then only a 32–18 vote.

The paired-comparison approach may be extended to include more than two samples or objects. If three or more objects are to be compared, the observer must be presented with all possible pairings. Again, a choice must be made each time. Such a method produces a rank order for the objects

Table 17-4 Results from preference test

	Pair	Preference
1	A vs. B	B
2	A vs. C	C
3	A vs. D	A
4	B vs. C	B
5	B vs. D	B
6	C vs. D	C

judged. This technique leads to the use of an ordinal scale of measurement.

Consider, for example, the same negative printed on four different brands of black-and-white paper with the goal to determine which print looks best. The letters A, B, C, and D identify the prints. The observer is presented with all possible pairings and each time is asked to state a preference. With four prints there is a total of six possible pairings. The results of such a test are shown in Table 17-4.

Before the rankings can be determined it is necessary to find out if the observer's judgments were consistent. Inconsistency is shown by the presence of one or more *triads* in the results. These triads (or inconsistencies) can be located by arranging the letters in a triangle and connecting them with short straight lines as shown in Figure 17-12. In example A, when prints A and B were compared, B was preferred so an arrow is drawn toward B. When prints A and C were compared, C was preferred so an arrow is drawn toward C. Likewise, for prints B and C, B was chosen and the arrow points toward it. The resulting pattern illustrates a consistent set of judgments. If, however, the three arrows move in a clockwise or counterclockwise direction as seen in Figures 17-12(B) and (C), an inconsistency has been

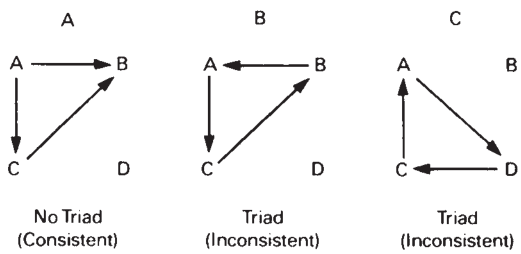


Figure 17-12 Location of triads (inconsistencies).

located. In Figure 17-12(C), for example, when prints A and C were compared, A was preferred; thus A is better than C. When prints A and D were compared, D was preferred; thus D is better than A. However, when prints C and D were compared, C was selected as being better, which is inconsistent with the earlier decisions.

Once an observer has been shown to be consistent, the rank order of preference can be determined. This is achieved simply by determining the number of times each print was selected. The data for this example are summarized in Table 17-5. The prints also may be located along a scale based upon their number of wins. In this example, print B was judged to be the best as it has the highest rank. Prints C, A, and D were the runners-up in that order. Thus simple statements of preference have been transformed into a rank order along an ordinal scale. In this example, only one observer was used—however, it would be possible to have many observers and average the results. Practically any subjective characteristic can be evaluated in this fashion.

Table 17-5 Number of wins and rank order of preference test results

Number of Wins	
A	1
B	3
C	2
D	0

D A C B

0 1 2 3

Rank Order

(Ordinal Scale)

Test Conditions

When performing subjective evaluations, perhaps the single greatest problem to overcome is the influence of the experimental conditions. It is critical that an observer's judgments be based only upon the properties of the objects being evaluated and not some outside factor such as a natural bias. For example, it is known that observers tend to prefer images placed on the left-hand side to images on the right. Also, images located above tend to be preferred over images placed below. In addition, there is a learning effect that occurs as a test continues. Consequently, images presented later in a test will be judged differently from those seen earlier, since the observer will be more experienced. The most common method for avoiding these difficulties is the randomizing of items; that is, the item to be judged must not be viewed consistently in the same position in space or time. If true randomization is achieved, each item will have an equal chance of being chosen, and the choice will be primarily the result of the observer's opinion of the item's inherent qualities.

Quality Control

Variability also occurs in production processes, such as in commercial photography labs. All manufacturers of goods are concerned with producing a high-quality product. That is what makes return customers. Just as you

would not return to a restaurant where you received a poor quality meal, you are not likely to continue to purchase a brand of film or print paper or return to a commercial lab that does not create consistent and repeatable results. For example, if you purchase two boxes of Brand X inkjet printer paper and the first prints with a magenta cast, the second with a cyan cast, you are not likely to try a third box.

All manufacturers of goods use some type of quality control procedure to ensure they are producing a quality product. A quality control process does not only monitor and test the finished product; it also involves monitoring the process that creates the product. Let us use the example of a monitor in a commercial custom lab used color correct digital images prior to sending them to a printer. There are many factors to track in this situation. A monitor will change with age, both in brightness and color balance, which will affect the final product. The visual judgments made on the monitor are also affected by the ambient lighting in the room. Just as the monitor changes with time, so does the color temperature and the brightness of the room lighting. All these factors need to be monitored and controlled to continue to produce a high-quality product.

In a commercial lab, a monitor used for custom color correction will be calibrated to some standard, both for brightness and color balance. The brightness of the monitor can be measured with a photometer and the color balance or spectral response with a spectrophotometer. We will concentrate on the brightness measurement only for our example, which will be measured at some set interval of time.

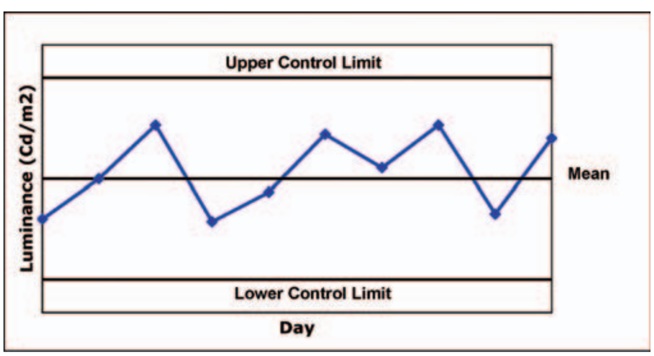


Figure 17-13 Quality-control chart example.

To begin a quality-control process, the factors that are going to be monitored and tracked must first be determined. Data must be collected to determine what the "normal" operating parameters are. When the operating parameters are as expected, the process is considered to be *in control* or *stable*. All parameters are going to have fluctuations because of change-cause variability. It is when the fluctuations are caused by cause-assignable variability that action must be taken to correct them.

A common method to track these factors is to set up a quality-control chart. An example of such a chart is provided in Figure 17-13. As can be seen in the example, there are several parts to a quality-control chart: the mean, the upper-control limit (UCL), and the lower-control limit (LCL). To determine these values, data is collected to establish the values for a stable process For this example we will use the brightness value measured from a monitor in units of Cd/m^2. Measurements will be taken twice each day. Each day is referred to as a group. The sub-group in this sample has two observations. The size of the sub-group is important in the calculation of the LCL and UCL.

The ISO Standard Viewing Conditions for Graphic Technology and Photography" (otherwise known as ISO 3664:2000) states that a digital picture that is to be edited on a display when there is no comparison made to hardcopy print, the white point luminance

should be between 75 and 100 Cd/m². In this example, the luminance value was calibrated to be 85 Cd/m².

To being new quality-control process a minimum of 30 data points are collected to determine if the process is stable so that monitoring can begin. Two types of control charts can then be constructed: a mean chart and a range chart. There are benefits to both. The range chart provides a crude estimate of variation in the process. The range of each subgroup is determined and tracked and provides information about short-term variability. The mean chart uses the mean of each subgroup. In a stable process, this will follow the normal distribution and provides information about long-term variability.

The construction of the mean control chart begins with the calculation of each subgroup mean. In the example here, this is the mean reading for each day. The mean of the means is then determined and used as the mean for the control chart. Next the UCL and the LCL are determined and added to the chart. Table 17-6 provides example data and the equations used to calculate the averages, UCL and LCL. Each subgroup mean is then plotted on the mean control chart as a function of time. When that is complete the chart is examined for one of four conditions that would indicate that the process is not in control, they are (1) an out of control point, (2) a run in the data, (3) a trend in the data or, (4) cycling of the data point. See Figure 17-14 for an example of each.

An *out-of-control* point is any data point that falls above the UCL or below the LCL. A point that is out of control is more than three standard deviations away from the mean and is unlikely to have been caused by chance. A *run* in the data is any five consecutive data points that fall either above or below the mean. A *trend* is five consecutive points that rise or fall. These points can cross the mean line simultaneously. The randomness expected in any process indicates that either a run or a trend would not be expected and may be caused by a problem with the process. *Cycling* occurs when five consecutive points alternately fall above and below the mean. Here again this pattern does not appear to be random and would require careful examination of the process.

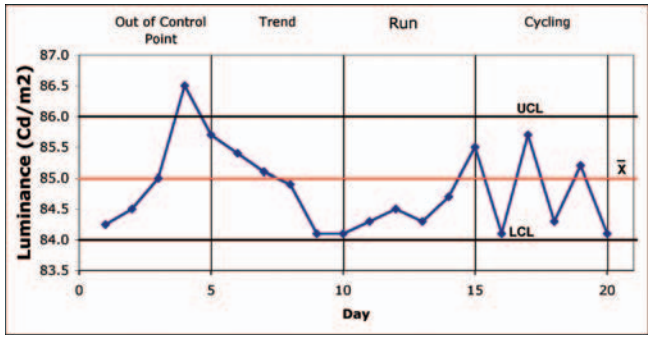


Figure 17-14 Sample of observations most likely not caused by chance

When a system displays out-of-control behavior, the source causing the behavior must be located and corrected. For the example here, the case may be that the measurement was made incorrectly, that this is operator error. The monitor settings may have been altered on the monitor, for example, the contrast may have been adjusted inadvertently. The calibration may need to be redone occasionally as the monitor ages, or perhaps the monitor has reached the end of its life span and needs replacing.

Figure 17-14 provides an example of all the calculations involved in creating quality-control cards. Although the sample provided here is quite simple, the process of quality control is not. There is a cost involved in implementing a control system. It takes equipment and manpower to do

Table 17-6 Example calculations for control chart construction

Day	X1	X2	X	R
1	85	83.5	84.25	1.50
2	85	84	84.50	1.00
3	86	84	85.00	2.00
4	87	86	86.50	1.00
5	86	86.5	86.25	0.50
6	85	84	84.50	1.00
7	84	84	84.00	0.00
8	83	84	83.50	1.00
9	84	84	84.00	0.00
10	85	85	85.00	0.00
11	86	85.5	85.75	0.50
12	87	86	86.50	1.00
13	87.5	86	86.75	1.50
14	87	86	86.50	1.00
15	86	85	85.50	1.00
16	85	85	85.00	0.00
17	84	84	84.00	0.00
18	84	84	84.00	0.00
19	83	85	84.00	2.00
20	84	84	84.00	0.00
21	85	85	85.00	0.00
22	86	86	86.00	0.00
23	87	85.5	86.25	1.50
24	87	86	86.50	1.00
25	86	86	86.00	0.00
26	85	85	85.00	0.00
27	84	84.5	84.25	0.50
28	83	84	83.50	1.00
29	85	85	85.00	0.00
30	85	85	85.00	0.00

$$\bar{\bar{X}} = \frac{\sum \bar{X}}{n} = \frac{2548.75}{30} = 84.96$$

$$\bar{R} = \frac{\sum R}{n} = \frac{19.0}{30} = 0.63$$

$$A_2 = 1.880 \quad D_3 = 0 \quad D_4 = 3.267$$

Chart of averages

$$\text{UCL} = \bar{X} + A_2\bar{R} = 84.96 + 1.88\ (0.63)$$
$$= 86.15$$

$$\text{LCL} = \bar{X} - A_2\bar{R} = 4.96 - 1.88\ (0.63)$$
$$= 83.77$$

Chart of means

$$\text{ULC} = D_4\bar{R} = 3.267\ (0.63)$$
$$= 2.07$$

$$\text{LCL} = D_3\bar{R} = 0\ (0.63)$$
$$= 0$$

properly. When an employee's time is diverted to this process they are not generating revenue for the company. However, not providing a quality product generates no revenue for the company. A balance must be found.

REVIEW QUESTIONS

1. The difference in contrast between grade 2 and grade 3 of the same printing paper would be identified as . . .

   A. chance-cause variability
   B. assignable-cause variability
   C. number-cause variability

2. Throwing two dice repeatedly and adding the numbers for each throw would be expected to produce a distribution pattern that is . . .

   A. rectangular
   B. basically rectangular, but with random variations
   C. triangular
   D. bell-shaped

3. We expect to find a normal distribution of data . . .

   A. always, when we have enough data
   B. when only human error is involved
   C. when only machine error is involved
   D. when chance is causing the variation
   E. when we made very precise measurements

4. A term that is not a measure of central tendency for a set of data is . . .

   A. average
   B. median
   C. range
   D. mean
   E. mode

5. If two normal distribution curves differ only in the widths of the curves, they would have different . . .

   A. means
   B. frequencies
   C. standard deviations
   D. inclinations

6. The minimum sample size that is recommended for a serious study of variability is . . .

   A. 1
   B. 2
   C. 30
   D. 100
   E. 1000

7. The selection of a sample from a population of data should be on the basis of . . .

   A. taking half from the beginning and half from the end
   B. taking all from the center
   C. a biased selection process
   D. a random selection process

8. The proportion of the total data included between one standard deviation above the mean and one standard deviation below the mean is . . .

   A. 50%
   B. 68%
   C. 86%
   D. 95%
   E. 99.7%

9. The series of *f*-numbers for whole stops on camera lenses represents . . .

   A. a nominal scale
   B. an ordinal scale
   C. an interval scale
   D. a ratio scale
   E. an exponential scale

10. In a paired comparison in which observers are asked to compare the graininess of three prints, viewed two at a time in all three combinations, one person selects A over B, B over C, and C over A. That person's choices were . . .

    A. consistent
    B. inconsistent

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appendix

A Conversion Units and Scales

Photograph by Professor Michael Peres, Biomedical Photographic Communications, Rochester Institute of Technology.

Conversion Units

Illuminance

Footcandle	Metercandle (lux)
1	10.76
0.0929	0

Luminace

Cd/square foot	Cd/square meter
1	10.76
0.0929	0

Fahrenheit, Celsius, and Kelvin Temperature Scales

F	C	K	
9440°	5230°	5500	Photographic daylight
5300°	2930°	3200	Photographic studio lamps
2780°	1530°	1800	Candlelight
1340°	727°	1000	Minimum for blackbody emission of light
212°	100°	373	Boiling point of water
98.6°	37°	310	Body temperature
68°	20°	293	Typical film development
32°	0°	273	Freezing point of water
0°	−17.8°	255	Zero Fahrenheit
−459°	−273°	0	Absolute zero

To change F to C:

$$C = \frac{5(F - 32)}{9}$$

To change C to F:

$$F = \frac{9C}{5} + 32$$

appendix

B Exposures, Depth of Field, Zone System, and Film Speed Information

Existing-Light Photography: Suggested Trial Exposures Based on ISO/ASA 400 Speed film

Subject-Lighting Condition	Camera Settings	
Photograph of a full moon	1/500 sec.	*f*/16
Photograph of a half moon	1/125 sec.	*f*/16
Subject illuminated by light of full moon	8 sec.	*f*/2
Skyline at sunset	1/125 sec.	*f*/11
Skyline just after sunset	1/125 sec.	*f*/8–5.6
Star trails	Time	*f*/2.8
Aurora borealis (Bright)	10–20 sec.	*f*/2
Aurora borealis (Medium)	40–80 sec.	*f*/2
Lightning bolts (Night)	Time	*f*/16
Underwater vs. above water, 5–15 feet	Open 1 stop	
Underwater vs. above water, 20–30 feet	Open 2 stops	
Bright signs at night	1/60 sec.	*f*/5.6
Fires	1/60 sec.	*f*/5.6–4
Fireworks	1/125 sec.	*f*/5.6–2
Night baseball, football, etc.	1/60 sec.	*f*/5.6–4
Night city streets and store windows	1/60 sec.	*f*/4–2.8
Moving traffic light streaks	1 sec.	*f*/11
Floodlit buildings	1/15 sec.	*f*/2.8–2
Niagara Falls lit by floodlights	1 sec.	*f*/2.8–1.4
Galleries	1/60 sec.	*f*/5.6–2
Offices, work areas	1/60 sec.	*f*/2.8–2
Television screen	1/8 sec.	*f*/11

Note: Other equivalent combinations of exposure time and *f*-number may be used. Extra exposure may be required to compensate for reciprocity effects with longer exposure times. (No compensation has been included in these numbers.)

Reciprocity Exposure and Development Compensation for General-Purpose Black-and-White Films

Indicated Exposure Time	Adjusted Exposure Time	Time Exposure Factor	Developing Time Adjustment
1/10 sec.	1/10 sec.	1.0	None
1 sec.	2 sec.	2.0	−10%
2 sec.	5 sec.	2.5	
3 sec.	9 sec.	3.0	
4 sec.	14 sec.	3.5	
5 sec.	20 sec.	4.0	
6 sec.	25 sec.	4.2	
7 sec.	31 sec.	4.4	
8 sec.	37 sec.	4.6	
9 sec.	43 sec.	4.8	
10 sec.	50 sec.	5.0	−20%
15 sec.	80 sec.	5.3	
20 sec.	120 sec.	6.0	
30 sec.	200 sec.	6.7	
40 sec.	300 sec.	7.5	
50 sec.	420 sec.	8.4	
60 sec.	560 sec.	9.3	−25%

F-Numbers	Shutter Speeds (seconds)
f/64	1/4000
f/45	1/2000
f/32	1/1000
f/22	1/500
f/16	1/250
f/11	1/125
f/8	1/60
f/5.6	1/30
f/4	1/15
f/2.8	1/8
f/2	1/4
f/1.4	1/2
f/1	1

Note: The *f*-numbers and shutter speeds above represent an increase in exposure at one stop (or 2×) for each change from top to bottom.

Relative Depth of Field for Different Focal Length Lenses on 35-mm Cameras, with the Same Object Distance and *f*-Number

Lens Focal Length	Relative Depth of Field
16 mm	9.8
20 mm	6.2
24 mm	4.3.
28 mm	3.2
35 mm	2.0
50 mm	1.0
75 mm	1/2.2
100 mm	1/4
135 mm	1/7.3
200 mm	1/16
400 mm	1/64

ISO Arithmetic and Logarithmic Film Speeds (1/3 stop increments)

Arithmetic	Logarithmic
6	9°
8	10°
10	11°
12	12°
16	13°
20	14°
24	15°
32	16°
40	17°
50	18°
64	19°
80	20°
100	21°
125	22°
160	23°
200	24°
250	25°
320	26°
400	27°
500	28°
650	29°
800	30°
1000	31°
1250	32°
1600	33°
2000	34°
2500	35°
3200	36°
4000	37°
5000	38°
6400	39°
8000	40°

Zone System Scene and Print Values

Scene	Value	Print
Dark	0	D_{max}
No detail		No detail
Dark	I	90% of D_{max}
Just detectable detail		Just detectable detail
Dark	II	Dark
Good detail	III	Good detail
Dark midtone	IV	
Midtone, 18% reflectance	V	Facsimile reflectance copying: D = 0.75
		Pictorial: Slightly lighter
Light	VII	Light
Good detail		Good detail
Light	VIII	D = 0.04 above paper white
Just detectable detail		Just detectable detail
Specular highlights	IX	Paper white
No detail		No detail
Light sources	X	Paper white
No detail		No detail

F/16 Rule

The camera exposure settings for an average scene in direct sunlight can be determined without an exposure meter by setting the lens at *f*/16 and using a shutter speed equal to the reciprocal of the ISO speed. Thus for an ISO setting of 125, the recommended settings would be 1/125 second at *f*/16, or any comparable combination.

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appendix

C Calculations and Basic Logarithms

Calculation of the Mean[1]

To determine the mean of a population or sample, all of the data are simply added together and divided by the number of pieces of data. For example, suppose that three tests of the resolving power of a film produced the following data: 59 lines/mm, 55 lines/mm, and 51 lines/mm. Using the formula

$$\bar{X} = \frac{\sum X}{n}$$

(where the symbol Σ means "sum of") the steps are:

1. Add up all of the X values: $(59 + 55 + 51 = 165)$.
2. Divide the total by the number of X values: (n) $(165 \div 3 = 55.0)$.

Notice that the mean is carried to one more decimal place than the original data. Thus, the mean resolving power for this experiment is 55.0 lines/mm.

Calculation of the Standard Deviation

Although the formulas for determining the standard deviation contain more terms, the calculations are relatively easy to do if taken step by step. To continue the example given above with resolving powers of 59, 55, and 51 lines/mm requires the use of one of the formulas for the sample standard deviation.

1. Determine the mean. Here $\bar{X}$ was found to be 55.0.
2. Determine the absolute difference (ignoring the sign) between each X value and the mean. In order, the differences are 4, 0, and 4.
3. Square each of the differences. The squares are 16, 0, and 16, respectively.
4. Add the squares. The total is 32. This is the numerator of the fraction under the radical sign.
5. Divide the total by the sample size minus 1: $(n - 1 = 2)$ $(32 \div 2 = 16)$.
6. Finally, find the square root of this value: $\sqrt{16} = 4.0$. The standard deviation is therefore 4.0 lines/mm, correctly taken to the same number of decimal places as the mean.

It is often convenient to set up the calculations in tabular form as shown:

$$s = \sqrt{\frac{\sum (X - \bar{X})^2}{n - 1}}$$

(Step 1)	(Step 2)	(Step 3)
X	$\lvert X-\bar{X}\rvert$	$(X-\bar{X})^2$
59	55.0–59 = 4	16
55	55.0–55 = 0	0
51	55.0–41 = 4	16
$\sum X = 165$		(Step 4)
$\bar{X} = 165 \div 3$		$\sum(X-\bar{X})^2 = 32$
$= 55.0$		
(Step 5)	(Step 6)	
$32 \div 2 = 16$;	$\sqrt{16} = 4.0 = s$.	

[1] Calculations should be carried out to one more significant figure than in the original data.

Basic Logarithms

Both interval scales of numbers (1-2-3-4-5-6-etc.) and ratio scales of numbers (1-2-4-8-16-32-etc.) are used in photography. Interval scales, for example, are found in thermometers and rulers. Ratio scales, for example, are used for *f*-numbers (*f*/2-*f*/2.8-*f*/4-*f*/5.6-*f*/8) where every second number is doubled, and ISO values (100-125-160-200-250-320) where every third number is doubled. Even though certain quantitative relationships in photography conform naturally to the ratio-type scale, there are disadvantages in using ratio scales of numbers in calculating and graphing. The disadvantages include the difficulty of determining the midpoint or other subdivision between consecutive numbers, and the inconvenience of dealing with very large numbers.

Using the logarithms of numbers in place of the numbers eliminates disadvantages of ratio scales by converting the ratio scales to interval scales. Mathematical operations are reduced to a lower level when working with logs, so that multiplication is reduced to addition, division is reduced to subtraction, raising a number to a power is reduced to multiplication, and extracting a root is reduced to division.

Logarithms, or logs, are derived from a basic ratio series of numbers: 10, 100, 1000, 10,000, 100,000, etc. Because $100 = 10^2$, $1000 = 10^3$, etc., the above series of numbers can be written as: 10^1, 10^2, 10^3, 10^4, 10^5, etc. The superscripts 1, 2, 3, 4, 5, etc. are called powers, or exponents, of the base 10. If we always use 10 as the base, the exponents are called logs to the base 10. By pairing the original numbers with the exponents, we have the beginning of a table of logs (see Table C-1).

Table C-1

Number	Logarithm
10	1
100	2
1,000	3
10,000	4

This table can be extended indefinitely downward. Since one million contains six tens as factors (10×10 $10 \times 10 \times 10 \times 10$), the log of 1,000,000 is 6. For any number containing only the digit 1 (other than zero), the log can be found by counting the number of decimal places between the position to the right of the 1 and the position of the decimal point. The log of 1,000,000,000 is therefore 9. The number whose log is 5 is 100,000, and 100,000 is said to be the antilog of 5. If the columns in Table C-1 are extended upward one step, the number 1 is added to the first column and the log 0 is added to the second. Thus the log of 1 is 0 and the antilog of 0 is 1.

We also need the logs of numbers between 1 and 10. Since the log of 1 is 0 and the log of 10 is 1, the logs of numbers between 1 and 10 must be decimal fractions between 0 and 1. The logs of numbers from 1 to 10 are listed in Table C-2. It is customary to write the log of a number to one more significant figure than the number itself. Thus the number 8 has one significant figure, and 0.90 (the log of 8) has two significant figures.

Table C-2 is used to illustrate some basic relationships between numbers and their logs:

1. $6 = 2 \times 3$. Note that the log of 6 is the sum of the logs of 2 and 3. When numbers are *multiplied*, their logs are *added*. The log of 10 equals the sum of the logs of 2 and 5.
2. $4 = 8 \div 2$. Note that the log of 4 is the difference of the logs of 8 and 2.

Table C-2

Number	Logarithm
1	0.00
2	0.30
3	0.48
4	0.60
5	0.70
6	0.78
7	0.85
8	0.90
9	0.95
10	1.00

When one number is *divided* by another, the log of the second is *subtracted* from that of the first. The log of 3 equals the difference of the logs of 6 and 2.

3. $4 = 2^2$. Note that the log of 4 is twice the log of 2. When a number is *squared*, the log is *doubled*. Similarly, $8 = 2^3$, and the log of 8 is three times the log of 2. When a number is raised to a *power*, the log of that number is *multiplied* by the power.
4. $\sqrt{9} = 3$. Note that the log of 3 is half the log of 9. Similarly, 2 is the cube root of 8, and the log of 2 is one-third the log of 8. When a *root* is taken of a number, the log of the number is *divided* by the root.

By the multiplication rule, the log of 50 is the log of 5 + the log of 10, or 0.70 + 1.00, or 1.70. Similarly, the log of 500 is 0.70 + 2.00, or 2.70; the log of 5000 is 3.70, etc. Also the log of 200 is 2.30, the log of 300 is 2.48, etc. All numbers in the hundreds have logs beginning with 2, all numbers in the thousands have logs beginning with 3, etc.

From this comes the concept that the log of a number consists of two parts: a whole number, determined by whether the original number is in the tens, hundreds, thousands, etc.; a decimal part determined by the digits. The whole number part of a logarithm is called the characteristic; it is solely determined by the location of the decimal point in the original number. The decimal part of a log is called the mantissa; it is found from a table of logs. To find the characteristic, count the number of places from a spot just to the right of the first digit of the number to the decimal point. For 500,000, the count is 5, and therefore the log begins with 5. The decimal part of the log, found in Table C-2, is 0.70, and the entire log is thus 5.70.

If a log is given, the antilog (the number corresponding to the log) is found by the reverse process—that is, use of the decimal part of the log to find the digits in the number and use the characteristic of the log to place the decimal point in the number. For example, to find the antilog of 3.78, note that 0.78 is the log of the number 6 in Table C-2. Therefore, 6 is the antilog of 0.78. The 3 in the log 3.78 indicates that the decimal point is moved three places to the right, changing the number from 6 to 6000.

We will now extend the basic log table to include decimal numbers between 0 and 1. In Table C-3, each number has one-tenth the value of the number just below it, whereas each log is reduced by a value of 1 for each step upward. Thus, the next number above 1 will be one-tenth of 1, or 0.1, and the log will be 1 less than 0, or −1, and so on. The basic log table can now be considered to extend indefinitely in both directions. Note the symmetry in Table C-3 about the number 1: for example, all numbers in the thousands have logs containing 3, and all numbers in the thousandths have logs containing −3.

Table C-3

Number	Logarithm
0.0001	−4
0.001	−3
0.01	−2
0.1	−1
1.0	0
10.0	1
100.0	2
1000.0	3
10000.0	4

(Note that the number column is identified as a ratio scale, which will never reach zero, and that the log column is identified as an interval scale.)

The logs of decimal fractions are found by the same procedure as that used for larger numbers. To find the characteristic (the whole number part of the log), count the number of places from the position to the right of the first nonzero digit to the decimal point. To find the mantissa (the decimal part of the log), locate the nonzero digit in the number column and note the corresponding value in the log column. For example, to find the log of 0.0003, the decimal point is 4 places to the left of the digit 3, so the log has a characteristic of −4. The mantissa is 0.48, opposite 3 in the number column in Table C-2.

The most awkward thing about logs is that there are several ways of writing the logs of numbers between 0 and 1. Most often the mantissa (a positive value) and the characteristic (a negative value) are kept separate and are written as an indicated unfinished computation. For example, three ways of writing the log of the number 0.004 are:

1. 0.60 −3, where 0.60 is the mantissa and −3 is the characteristic. This is the most direct form, but it is not often used.
2. 7.60 −10, where 0.60 is the mantissa and the combination 7 − 10 (which is equal to −3) is the characteristic. This form, which is always written as some number minus 10, is the form most commonly used outside photography.
3. $\bar{3}.60$, where 0.60 is the mantissa and $\bar{3}$ is the characteristic. The minus sign is placed over the 3 to emphasize that only the 3 is negative, not the 0.60. This form is referred to as bar notation, and the log above is read "bar three point six zero." This form is found in many photographic publications, but the scientific calculator is making bar notation obsolete.
4. With a scientific the log of 0.004 can be written as −2.40.

The procedure for finding the antilog of a log having a negative characteristic is the same as described above for positive logs, except that the decimal will be moved to the left in the number rather than to the right. With $\bar{3}.60$ as the log, for example, the antilog of 0.60 is 4, and moving the decimal three places to the left produces 0.004. Thus, the antilog of $\bar{3}.60$ is 0.004.

An expanded table of logs for numbers from 1.0 to 10.0 to one decimal place, with logs to three decimal places, is provided in Table C-4.

Logarithms and the Use of a Calculator

The use of scientific hand calculators greatly eases the tasks of determining logs and anti- (or inverse) logs. To find the log of a number greater than 1, simply enter the number and then press the key labeled "LOG." The answer will appear on the display. To

Table C-4 Abbreviated table of logarithms

Number	Logarithm	Number	Logarithm	Number	Logarithm
1.0	0.000	5.5	0.740	0.0001	−4
1.1	0.042	5.6	0.748	0.001	−3
1.2	0.080	5.7	0.756	0.01	−2
		5.8	0.763	0.1	−1
1.26	0.100	5.9	0.771	1	0
				10	1
1.3	0.114	6.0	0.778	100	2
1.4	0.147	6.1	0.785	1000	3
		6.2	0.792	10,000	4
1.414	0.150	6.3	0.799	100,000	5
		6.4	0.806		
1.5	0.175			2	0.301
		6.5	0.813	20	1.301
1.6	0.204	6.6	0.819	200	2.301
1.7	0.230	6.7	0.826	2000	3.301
1.8	0.255	6.8	0.832		
1.9	0.278	6.9	0.839		
2.0	0.301	7.0	0.845		0.301–1
2.1	0.322	7.1	0.851		or
2.2	0.342	7.2	0.857	0.2	9.301–10
2.3	0.361	7.3	0.863		or
2.4	0.390	7.4	0.869		$\bar{1}.301$
					or
2.5	0.398	7.5	0.875		−0.69
2.6	0.415	7.6	0.881		
2.7	0.431	7.7	0.886		
2.8	0.447	7.8	0.892		
2.9	0.462	7.9	0.898		
3.0	0.477	8.0	0.903		
3.1	0.491	8.1	0.908		
3.2	0.505	8.2	0.914		
3.3	0.518	8.3	0.919		
3.4	0.532	8.4	0.924		
3.5	0.544	8.5	0.929		
3.6	0.556	8.6	0.934		
3.7	0.568	8.7	0.940		
3.8	0.580	8.8	0.944		
3.9	0.591	8.9	0.949		
4.0	0.602	9.0	0.954		
4.1	0.613	9.1	0.959		
4.2	0.623	9.2	0.964		
4.3	0.634	9.3	0.968		
4.4	0.644	9.4			
4.5	0.653	9.5	0.978		
4.6	0.663	9.6	0.982		
4.7	0.672	9.7	0.987		
4.8	0.681	9.8	0.991		
4.9	0.690	9.9	0.996		
5.0	0.699	10.0	1.00		
5.1	0.708				
5.2	0.716				
5.3	0.724				
5.4	0.732				

Table C-5

Number	Bar Log	Negative Log
0.0002	$\bar{4}.3$	−3.7
0.002	$\bar{3}.3$	−2.7
0.02	$\bar{2}.3$	−1.7
0.2	$\bar{1}.3$	−0.7
2	0.3	0.3
20	1.3	1.3
200	2.3	2.3
2000	3.3	3.3

find the antilog of a positive log, simply enter the log value and press the keys labeled "INV" and "LOG" in that order. The answer will appear on the display.

Note: On some calculators, there is no key labeled "INV." For these calculators, the key labeled "10^x" should be substituted for the entire "INV" and "LOG" key sequence.

Example

Problem: Find the log of 0.004.
Solution: Enter the number 0.004 into the calculator and press the key labeled "LOG"; the answer of −2.39794 rounded to −2.40 is shown in the display.
Answer: The log of 0.004 is −2.40.

To find the antilog of a totally negative log, the above procedure is reversed. The totally negative log is entered into the calculator and the keys labeled "INV" and "LOG" are pushed, in that order.

Example

Problem: Find the antilog of −2.40.
Solution: Enter the value −2.40 into the calculator and press the keys labeled "INV" and "LOG" in that order; the number 0.003981 appears in the display and is rounded to 0.004.
Answer: The antilog of −2.40 is 0.004.

Since the bar notation system is often encountered in photographic publications, a procedure for using a calculator with this system is given below.

To find the log of a number less than 1.0 expressed in bar notation using a calculator:

1. Move the decimal point to the right of the first nonzero digit and count the number of places it was moved. The number of spaces moved is the characteristic it will be, but assigned a negative value.
2. Enter the number (with the decimal moved) in the calculator and press the button labeled "LOG"; the value that appears in the display is the mantissa of the number and will be a positive value.

Example

Problem: Find the log of 0.2.
Solution:

1. The decimal point is moved one place to locate it to the right of the first nonzero digit (2); thus the characteristic is bar one ($\bar{1}$).
2. Enter the number 2.0 in the calculator and press the button labeled "LOG"; the value of 0.30 appears and is the mantissa.

Answer: The log of 0.2 is $\bar{1}.30$.

To find the antilog (inverse log) of a log expressed in bar notation using a calculator:

1. Enter the mantissa of the log into the calculator and press the buttons labeled "INV" and "LOG," in that order; the value that appears on the display will contain all of the digits of the antilog with the decimal point immediately to the right of the first digit.

2. Locate the decimal point at the correct position by moving it to the left the number of places indicated in the characteristic.

Example

Problem: Find the antilog of $\bar{1}.30$.
Solution:

1. The mantissa of 0.3 is entered in the calculator and the keys labeled "INV" and "LOG" are pushed and the value 1.9952623 appears, which is rounded to 2.0
2. The characteristic is bar one, indicating that the decimal should be moved to the left one position, giving 0.2.

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appendix

D Tristimulus Value and Chromaticity Coordinate Calculations

To determine the tristimulus values X, Y, and Z for an object, the spectral power distribution of the illuminant, S_λ, the object's spectral reflectance factor, R_λ, and the CIE standard observer color-matching functions, $\bar{x}_\lambda$, $\bar{y}_\lambda$, and $\bar{z}_\lambda$, are integrated together as follows:

$$X = k\sum_\lambda S_\lambda R_\lambda \bar{x}\Delta\lambda$$

$$Y = k\sum_\lambda S_\lambda R_\lambda \bar{y}\Delta\lambda$$

$$Z = k\sum_\lambda S_\lambda R_\lambda \bar{z}\Delta\lambda$$

$$k = \frac{100}{\sum_\lambda S_\lambda \bar{y}\Delta\lambda}$$

The S, R and either, $\bar{x}$, $\bar{y}$, and $\bar{z}$, are multiplied together at each wavelength sampled. The $\Delta\lambda$ represents the wavelength interval that measurements are made at. Although the interval can vary, it is usually 10 or 20 nanometers for objects. The Σ_λ indicates that the products of multiplications are summed across wavelengths measured. The k is a normalizing constant.

The CIE color matching functions are provided at 1 nm increments from 360 to 830 nm. The ideal situation would be that the measurements of the object and illuminant be done over the same range using the same interval. Most spectrophotometers are not designed this way, instead they typically will range from 400 to 700 nm in increments of either 10 or 20 nm.

When the tristimulus values have been calculated the chromaticity coordinates can then be determined with the following equations:

$$x = \frac{X}{(X + Y + Z)}$$

$$y = \frac{Y}{(X + Y + Z)}$$

$$z = \frac{Z}{(X + Y + Z)}$$

It is worth noting that $x + y + z = 1$.

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Answers to Review Questions

Question Number	Chapters																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	A	D	C	A	A	B	C	D	D	C	D	B	C	D	D	E	B
2	B	A	B	D	E	B	B	E	B	B	A	A	C	B	B	B	C
3	C	C	B	C	D	C	C	D	C	A	A	B	C	A	D	B	D
4	A	C	C	B	A	D	C	C	C	C	C	B	D	C	B	C	C
5	C	A	A	D	E	D	B	E	D	A	A	C	A	E	B	C	C
6	A	A	D	A	D	C	A	A	B	C	B	B	B	E	C	C	C
7	B	C	B	B	C	C	B	C	D	A	E	C	D	D	D	A	D
8	A	D	C	B	B	D	C	B	A	A	D	D	A	A	B		B
9	D	C	B	E	B		B	C			A	D	B	D			D
10	C	A	C	B	E			D			A	D		C			B
11	D	C	D	E	D							A		B			
12	B	C		D	B							C		A			
13	B	A		B	C							B		B			
14	C	A		A	D							E		C			
15	E	B		B	C									D			
16		A		C	B									D			
17		A		B	D									C			
18		C		B	D									B			
19		C		A	C									E			
20		C		C	B									D			
21				C	B									B			
22				A	D									E			
23				A	A												
24				D	D												
25				C	A												
26				B	C												
27				D	B												
28				B	D												
29				B	A												
30				C	D												
31					B												

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